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A Study of an Advanced Variable Cycle Diesel as Applied to an RPV

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Evaluation of an RPV Variable Cycle Diesel Engine

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A variable cycle diesel is examined for use in an unmanned long endurance RPV. Engine configuration studies are made and a possible installation arrangement developed. Installed performance projections are made and a long endurance RPV mission fuel, installed engine weight and propeller performance estimates made along with several aircraft installation drawings. It was found that the final engine configuration performed the specified mission with a total fuel and installed engine weight fraction of only 24 percent of the vehicle Take Off Gross Weight. The mission was evaluated at a cruise altitude of 65000 feet and an engine configuration suitable for use at 85000 feet was also investigated.

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SUMMARY

This report covers the work done by the DieselDyne Corporation for the Defense Advanced Research Projects Agency (DARPA) under study contract DAAH01-88-C-0660. The study consisted of evaluating the installation and performance of an Advanced Variable Cycle Diesel (AVCD) Engine applied to a High Altitude Long Endurance (HALE)/ Unmanned Air Vehicle (UAV) system. The document from the DARPA program manager specifying mission, vehicle characteristics and power requirements is shown in Appendix A of this report.

Four separate engines were evaluated for the vehicle and the final engine is thought to be the most fuel efficient possible within reasonable weight and system complexity constraints. Descriptions of each of the engine systems and their installed mission fuel burns are included in the report along with an installation evaluation of the final engine in a hypothetical HALE/UAV. The installation results include drawings, system weights, propeller characteristics and performance, and an assessment of the heat exchanger requirements.

Appendix C includes figures and a textual description of the figures from the Interim Oral Review presented at the DARPA offices at Arlington, Virginia on November 22, 1988. The Oral Review results represent the mid-study status and are included for completeness.

It is felt that no technological barriers exist in the deployment of such an engine system in terms of requisite performance levels but that no suitable exhaust driven turbocompressors now exist and the required AVCD engine would need to be developed. It is also felt that even higher cruise altitudes than specified for the current study are attainable with the same basic engine hardware, but that a higher pressure ratio turbocompressor and engine-driven supercharger would be required. In line with this last statement, a brief description of the engine system to efficiently attain an 85000 foot altitude cruise capability is also provided in the report.

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1.0 INTRODUCTION

Between World Wars I and II the Junkers Company of Dessau, Germany developed a series of very compact, fuel efficient aircraft diesel engines. The JU205 engine employed an engine driven supercharger and was considered a "ground" engine and was extensively used on Lufthansa airline aircraft and other long endurance, low altitude craft such as flying boats. Although accurate records are not available, it is believed that more than 1500 of the JU205 engines were manufactured. The Junkers Company also developed an "altitude" version of the JU205 that was designated the JU207. This engine ran at higher speeds than the JU205 and it employed an exhaust gas driven turbocharger in series with the engine driven supercharger and a charge air aftercooler. Several hundred of these engines were built and applied primarily to the JU86 series of high altitude bomber/reconnaissance aircraft. The JU86P, for instance, was capable of sustained flight at altitudes in excess of 40000 feet in 1940 and was therefore immune from attack from existing Allied fighter aircraft.

Improved models of the JU207 were fitted to a JU86R series of aircraft and cruise altitudes of 47250 feet were routinely achieved during 1942. A final series of diesel engines (designated JU208) was under development when the high altitude engine program was canceled. This engine was designed to produce 1500 SHP at take-off and 1100 SHP between 40000 and 50000 feet altitude and was to be fed compressed air from a fuselage mounted Daimler-Benz DB605T engine driving a two stage blower. It was anticipated that the resulting JU86R-3 aircraft would be capable of a service ceiling of 52500 feet.

From this earlier German work, the DieselDyne Corporation has developed preliminary designs for an Advanced Variable Cycle Diesel (AVCD) engine based on the Junkers aircraft diesel layout. The dual crankshaft, ported 2-stroke design has been retained and a cross section of the resulting engine is shown in Figure 1-1. One important advancement over the Junkers' work has been the incorporation of means to vary the significant operating parameters of the engine while it is running. The parameters that can be varied are shown in Figure 1-2 and include the ability to vary the compression ratio, injector timing and intake/exhaust port timing. In addition, the ability to control the boost pressure, exhaust back pressure and scavenge flow permits the complete control and adjustment of the engine to widely varying ambient conditions. This capability prompted investigation of the AVCD as an extreme altitude engine that might be suitable as a power plant for currently envisioned HALE/UAV systems.

Another significant advantage over the prior German work has been the post-war development of high pressure ratio compressors in the 12 to 24:1 range. When coupled to a modern exhaust gas driven turbine, these turbocompressors permit the operation of an AVCD engine at altitudes in excess of 100000 feet as shown in Figure 1-3. For this case, a 24:1 turbocompressor was operated in series with a 4:1 engine driven supercharger in conjunction with an intercooler and aftercooler. Figure 1-4 illustrates an extreme altitude AVCD engine system that was used for the Figure 1-3 engine study and was also retained for this current study. Exhaust back pressure and scavenge flow control is maintained by the variable area exhaust jet nozzle. Turbocompressor operating control is also achieved by the variable exhaust nozzle thereby eliminating the need for a wastegate.

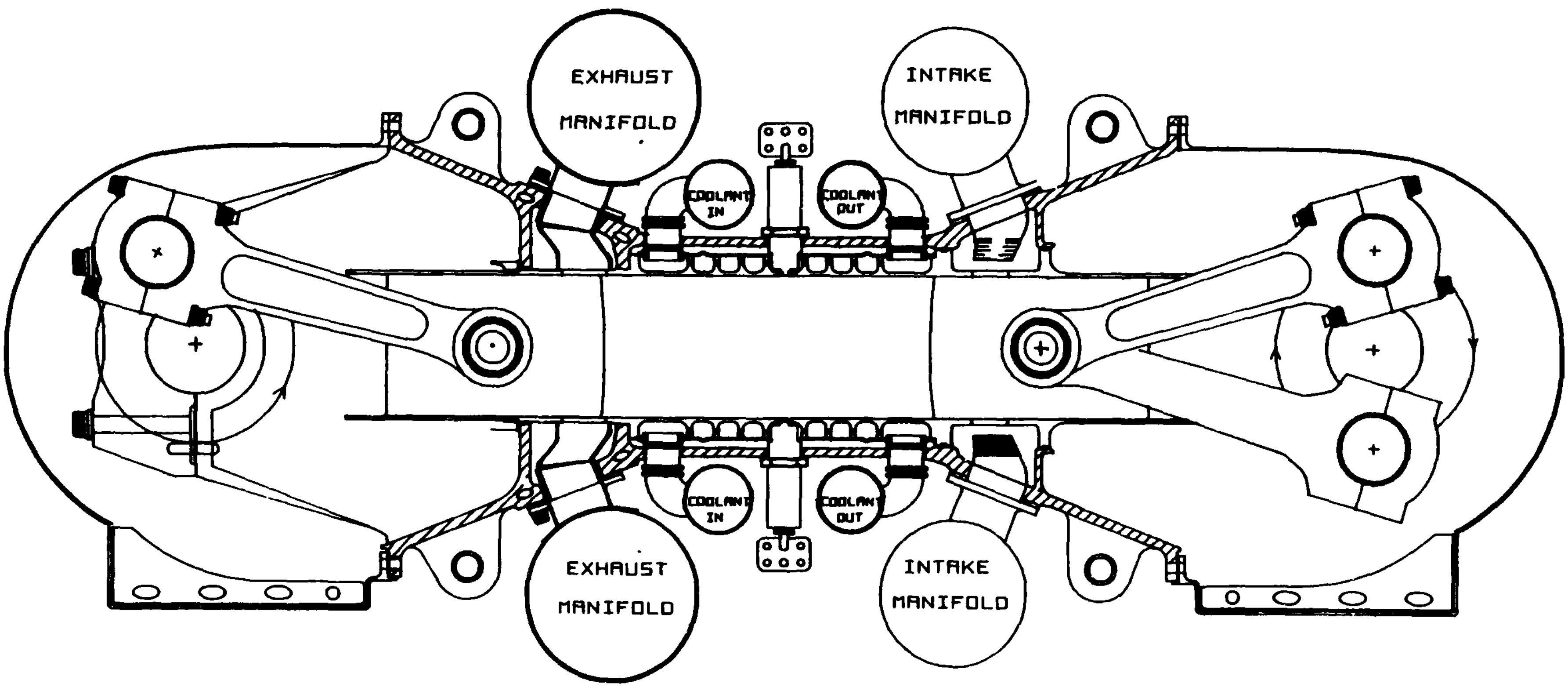

Figure 1-1 AVCD Engine Cross Section

- VARIABLE BOOST
- VARIABLE C/R
- VARIABLE PORT TIMING
- VARIABLE INJ. TIMING
- VARIABLE EXH. CONTROL
- VARIABLE SCAVENGE CONTROL

Figure 1-2 AVCD Variable Cycle Concept

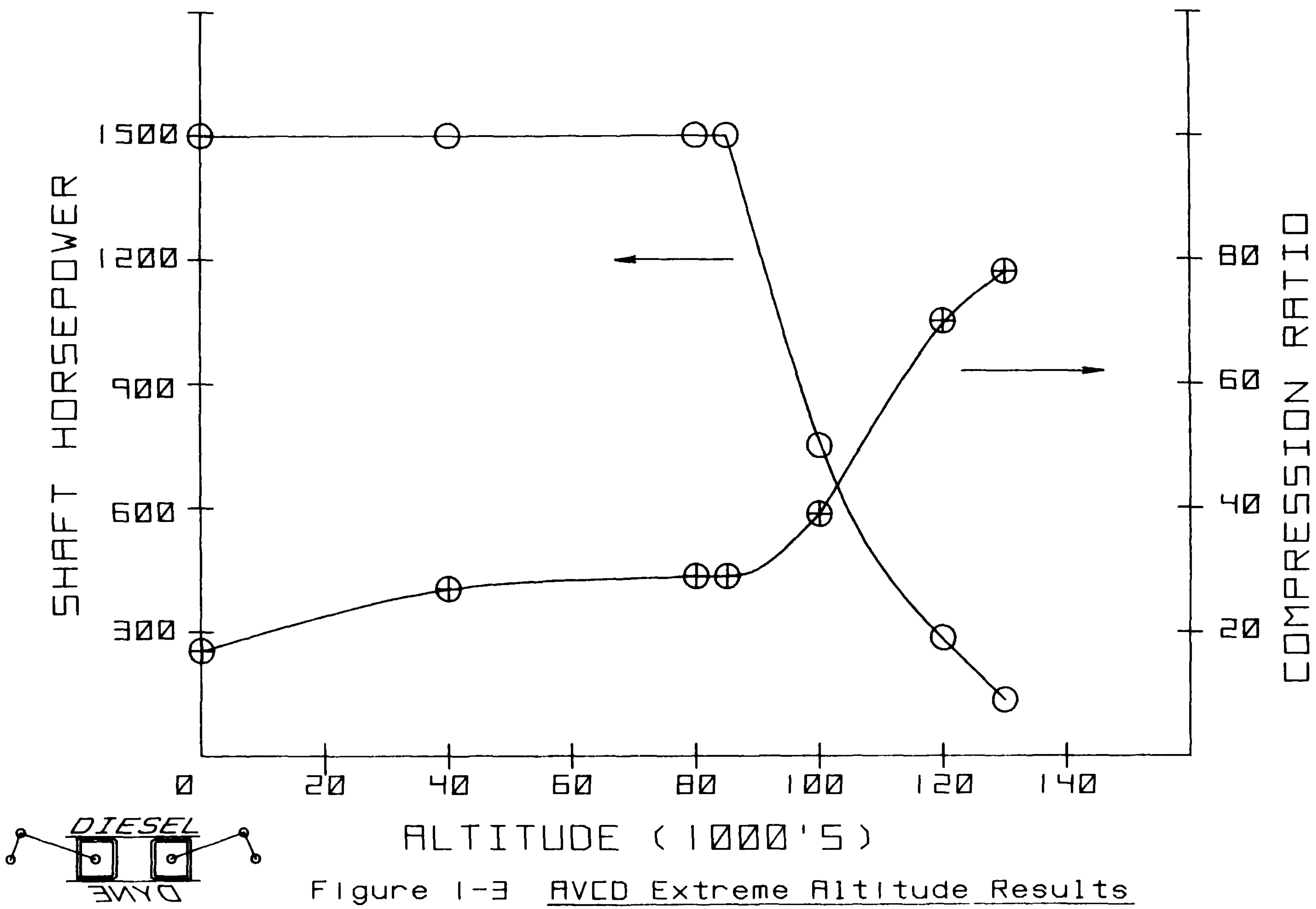

Figure 1-3 AVCD Extreme Altitude Results

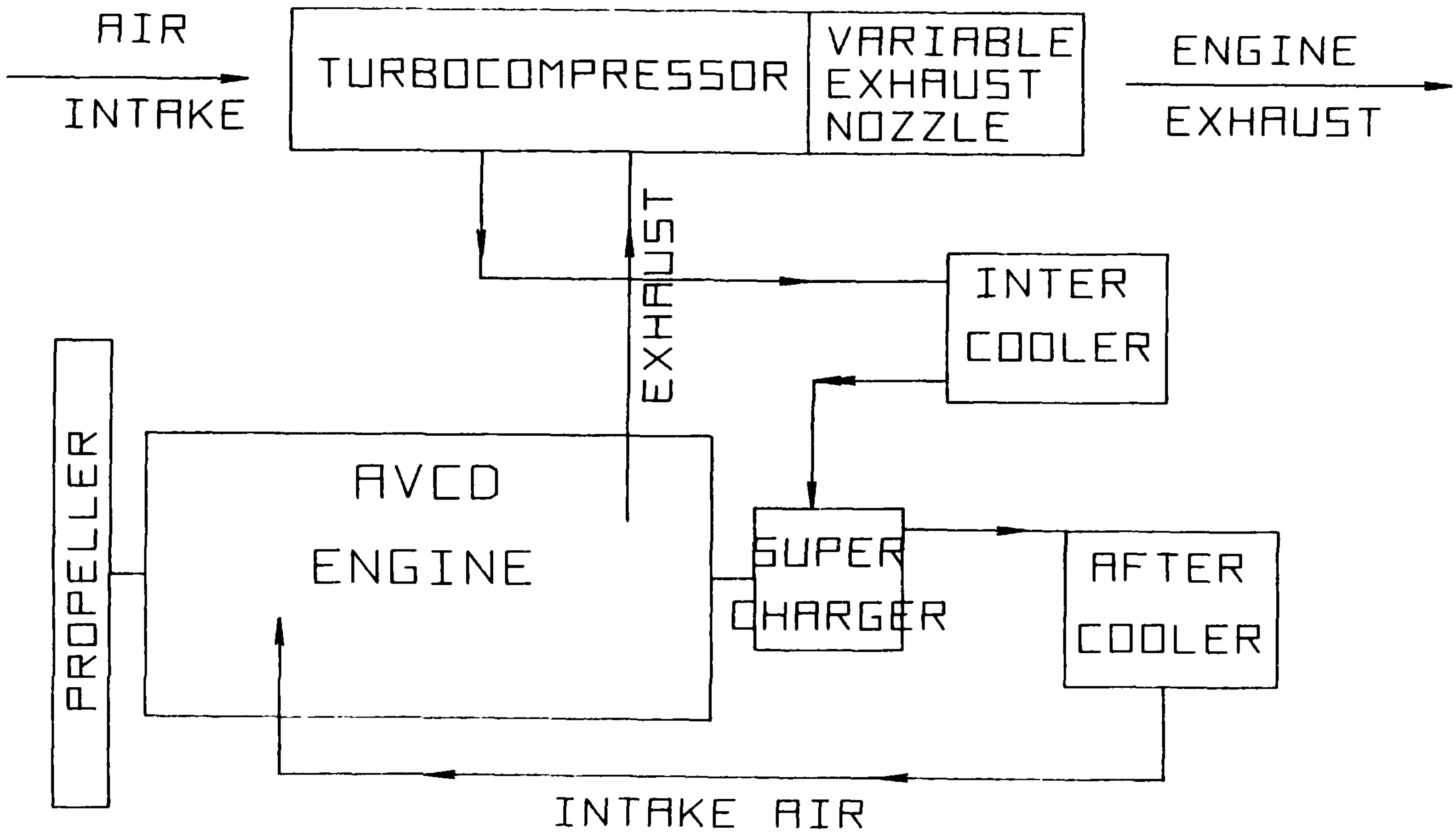

Figure I-4 Extreme Altitude Engine System

Performance analysis of the AVCD engine installed in the flight vehicle was computed through the use of a DieselDyne proprietary simulator code called the Diesel Analysis Program (DAP). This code has been developed over the past four years and incorporates many features to permit the analysis and prediction of operating characteristics of an AVCD engine. Internal loss correlations and flow characteristics have been based on existing JU205 and JU207 engine data and the DAP code has been shown to predict both ground and altitude performance for both Junkers engines with good accuracy.

2. OBJECTIVES

The objective of the current study was to evaluate the performance and installation of an AVCD engine in a typical HALE/UAV system as defined by the DARPA program manager. Figure 2-1 states the overall purpose of the study in an abbreviated form. The following technical Task statements from the original study proposal illustrate the extent and intent of the study.

Task I - Selection of Operational Requirements, Engine Size and Associated Equipment.

Task II - Modification of Engine, Control Logic, and Determination of Required Subsystem Component Performance Levels.

Task III - Total System Assessment including Projected Propeller Performance, Firewall Forward Weight, Sizing of Subsystem Equipment, and Installation Drawing.

Task IV - Complete Engine System Performance Characterization for Selected Altitude Increments and Performance Derivatives at Cruise Power Settings.

STUDY AN AVCD IN A RPV

- DETERMINE OPERATING CHARACTERISTICS
- CONFIGURATION
- ENGINE CONTROL PHILOSOPHY
- PERFORMANCE
- INSTALLATION
- WEIGHT

Figure 2-1 Study Purposes

3.0 CONCLUSIONS

A very compact (see Figure 3-1) AVCD engine can be configured to efficiently satisfy the requirements of the 65000 foot cruise HALE/UAV system as defined by the DARPA program manager in the Appendix A document. The engine system can be installed in a hypothetical HALE/UAV air frame power plant bay with current state of the art performance from ancillary equipment. A pre-compression system consisting of a 12:1 exhaust driven turbocompressor in series with a 1.35:1 positive displacement Roots-type blower with an intercooler and aftercooler is required to supply adequate intake air and pressure. The total installed power plant weight (2 engines) with associated equipment amounts to 2198 pounds. Total fuel burn for the specified mission is estimated to be 6447 pounds. The fraction of TOGW for the installed power plants and mission fuel would be .247 of the initial 35000 pound vehicle weight.

A 14 foot 4 bladed propeller for each engine and 4 fin-tube heat exchangers for rejecting engine coolant heat, turbocompressor air intercooling, supercharger aftercooling and engine oil heat is required. A frontal area of approximately 15 square feet for the heat exchangers is needed for the high altitude operation at 65000 feet.

Although only state of the art performance levels are required for the engine ancillary equipment, there is no available exhaust driven turbocompressor extant that would satisfy the study defined configuration and performance. Likewise, the AVCD engine described in the study would have to be developed. If an adequate development program were to be funded, it would take 3 to 5 years to produce an AVCD engine with sufficient reliability to perform the envisioned HALE mission. Using an existing compressor and developing the required turbine would take a minimum of two years before a flight ready turbocompressor fitting the needs of the study AVCD engine system would be ready. All other major engine system components could be obtained with little or no development.

One of the favorable characteristics of the AVCD engine that has been seen in the analytic results is that once the vehicle is at an adequate altitude to permit disengaging of the engine driven supercharger, low specific fuel consumption is attained right up to the ultimate design cruise altitude. In fact, the 65000 foot engine peak thermal efficiency is reached at about 50000 feet altitude. Therefore, good mission fuel economy is possible at lower than design cruise conditions. This provides added flexibility for carrying out HALE/UAV missions at lower than ultimate design cruise altitude.

An 85000 foot cruise HALE/UAV system engine can also be configured that produces the same installed power as the defined mission requires. The changes needed to permit the higher altitude cruise is a doubling of the turbocompressor and supercharger pressure ratios to 24:1 and 1.7:1 respectively. The heat exchanger frontal area more than doubles to 36 square feet per engine and the prop diameter increases to approximately 20 feet. However, with the specified changes essentially the same Brake Specific Fuel Consumption (BSFC) performance can be expected as with the 65000 foot design engine.

Use of an AVCD engine has also been found to reduce the pre-compression levels and system complexity to sustain extreme altitude power levels. This is due to the ability of the AVCD engine to adjust its compression ratio in response to

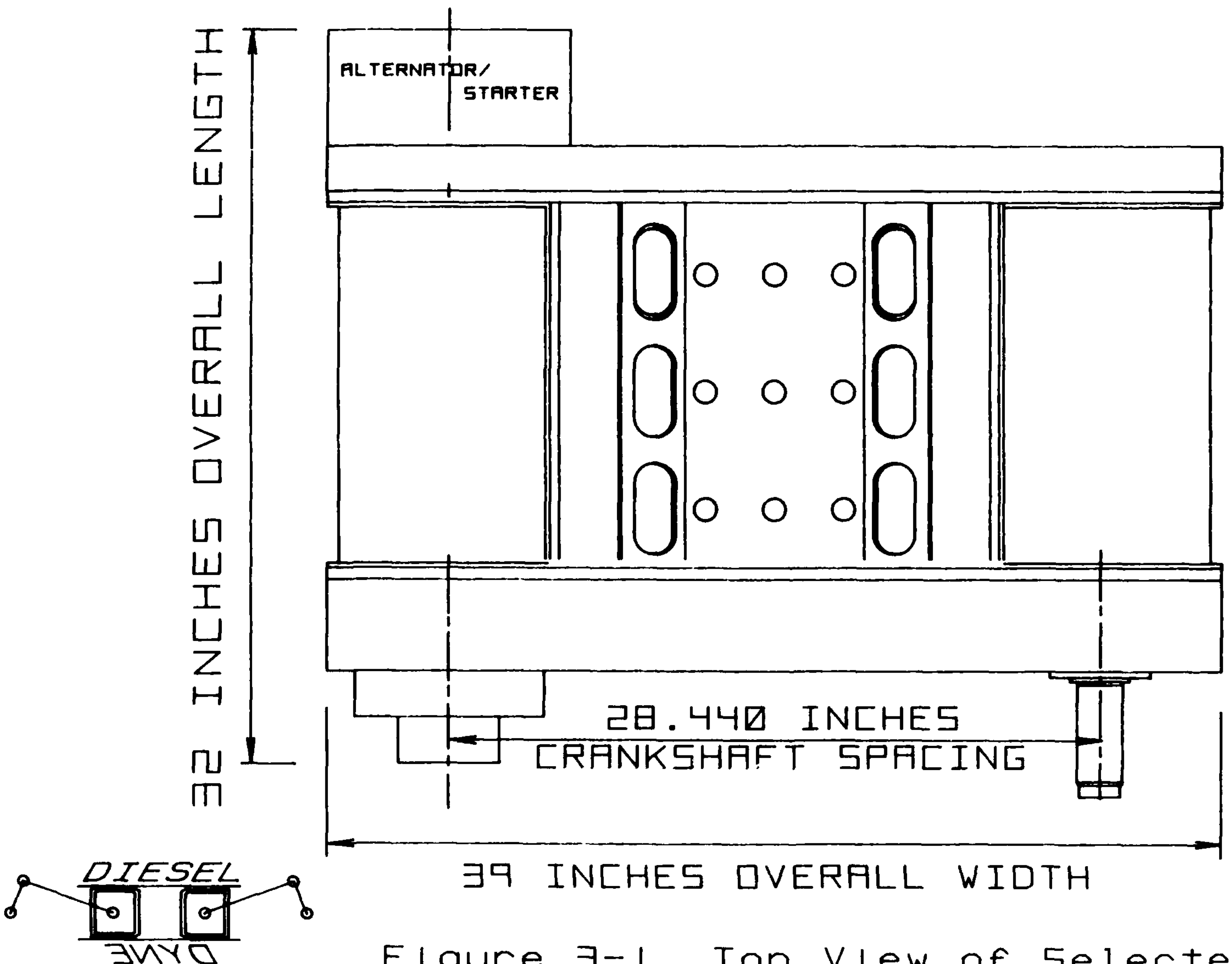

Figure 3-1 Top View of Selected Engine

pre-compression conditions as shown in Figure 3-2 (taken from the third study engine control schedule). The last table shown in Appendix C illustrates this by comparing the 85000 foot cruise AVCD engine with a comparable fixed cycle extreme altitude gasoline engine from another study. The AVCD system required approximately 50% less pre-compression, 1 less compressor, 3 less turbines, no turbo-compounding gear or wastegate controls to achieve the required power levels. In addition, the AVCD engine performance was based on compression efficiency levels from .9 to 8% lower and a turbine efficiency level 7.5% less than the fixed cycle engine's. In spite of the reduced complexity and ancillary equipment performance levels, AVCD equivalent BSFC was projected to be lower than the fixed cycle gasoline engine system.

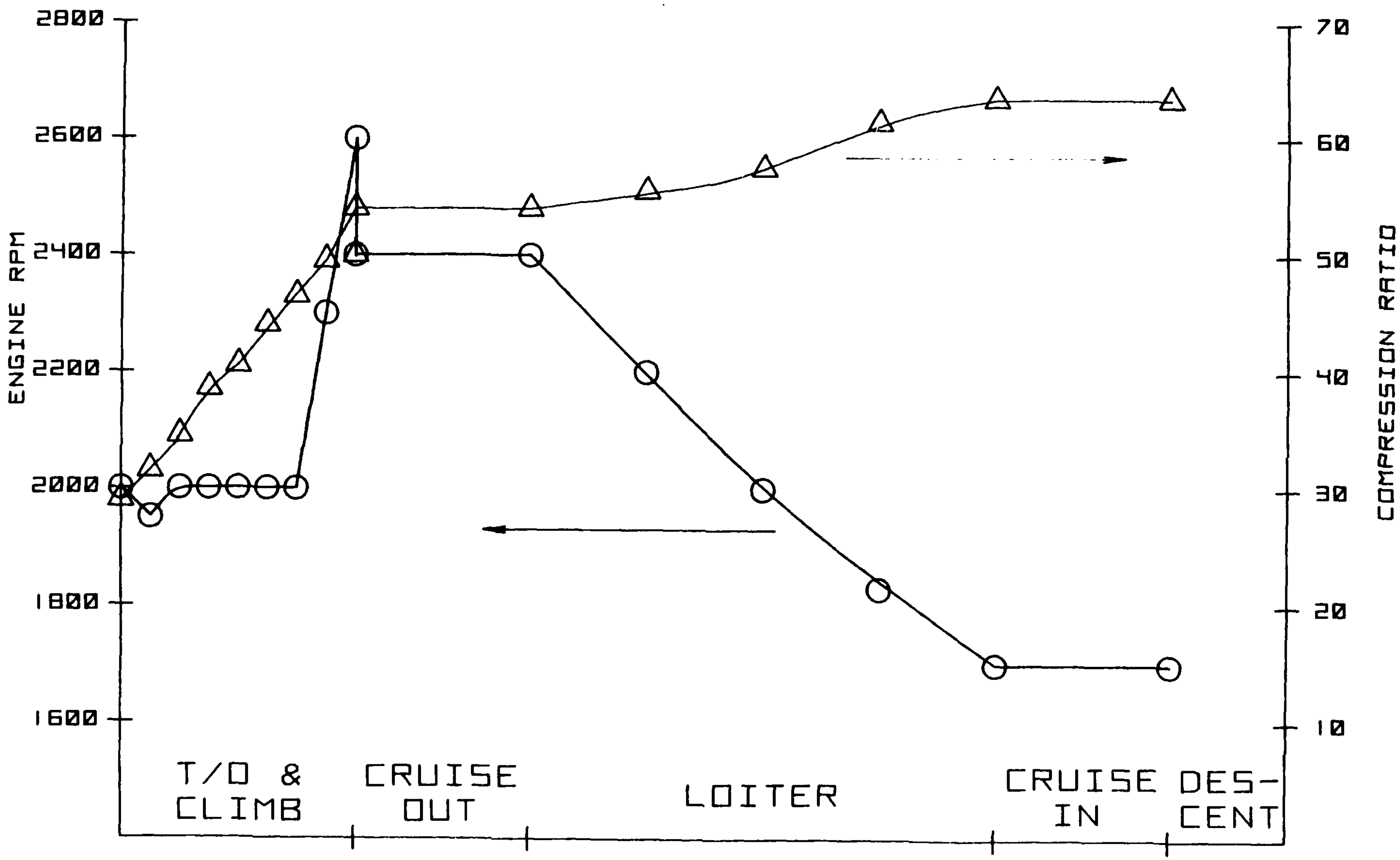

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Figure 3-2 Engine RPM/Compression Ratio Schedule

4.0 RECOMMENDATIONS

It is recommended that a single cylinder demonstrator engine program be undertaken to verify the predicted performance of a high altitude AVCD engine. This can be done relatively quickly and would provide a running start on a development program to produce a full scale engine for a deployed HALE/UAV system.

It is also recommended that a consensus be developed among potential end-users of projected HALE/UAV systems to define ultimate mission, payload capability and cruise altitudes. When this has been accomplished, then development of a suitable turbocompressor that would provide appropriate compression levels and air flow for the required AVCD altitude engine could be started along with the full scale AVCD engine itself. Since the program to produce properly matched turbocompressors and engines would require relatively long lead times , HALE/UAV variations in size and mission could be handled by varying the number of installed engines rather than trying to develop multiple versions of the engine system.

The hypothetical HALE/UAV system, shown in Figure 4-1, used in the installation studies illustrates this solution by utilizing a fore and aft engine arrangement. This basic cooling/engine bay could be retained with one or two engines installed. With a modification of wing form (primarily span), a 5000 to 35000 pound TOGW vehicle could perform short to extreme range missions at cruise altitudes of from 40 to 100000 feet altitude.

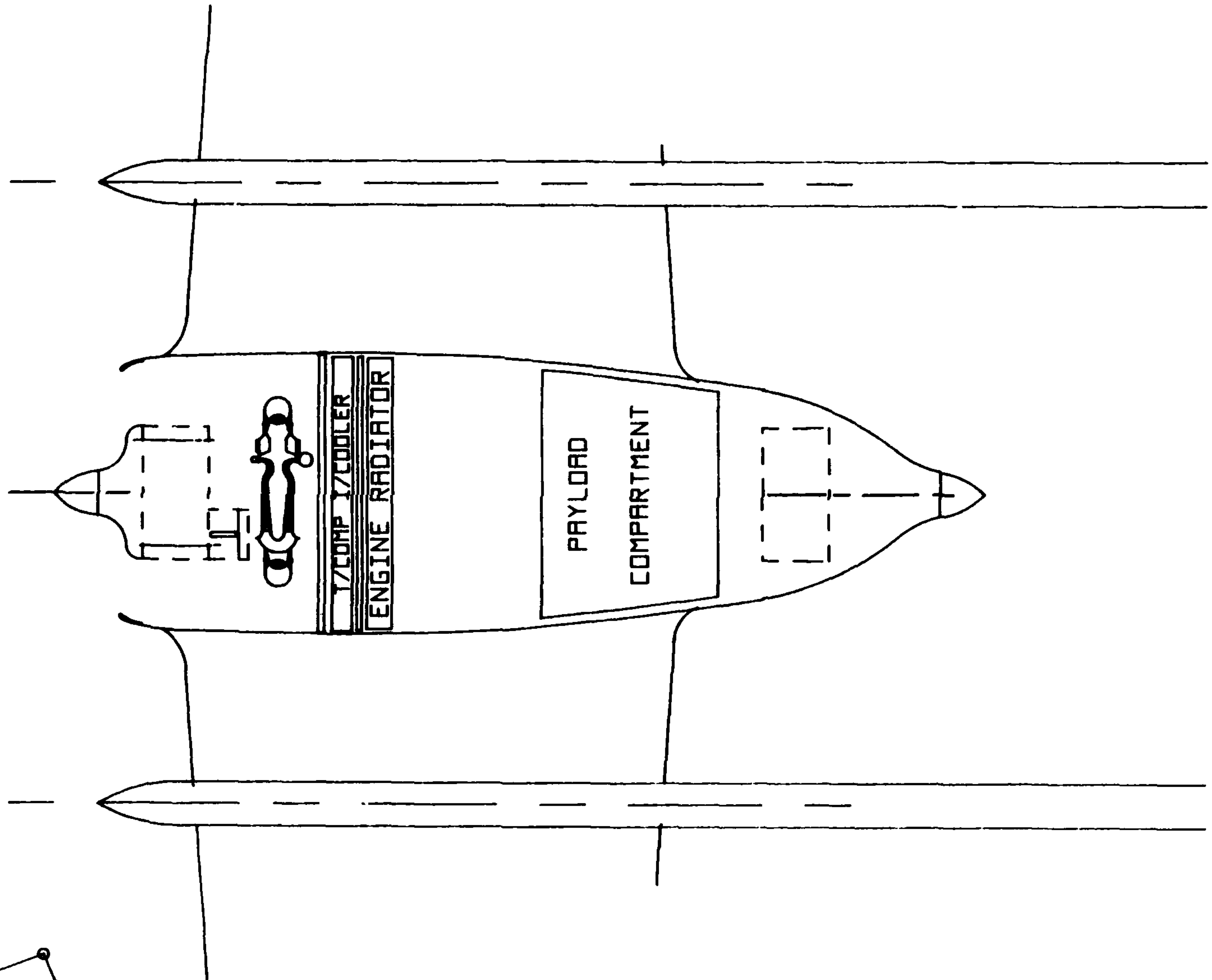

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Figure 4-1 HALE/UAV Study Configuration

5.0 DISCUSSION

5.1 Mission and Engine Size Selection

Based on the initial mission and vehicle definition supplied in the Appendix A letter, a set of requirements and vehicle characteristics was developed as shown in Figure 5-1. A maximum SHP of 250 during the take-off and climb flight segments coupled with a 210 to 44 SHP variation during the 65000 foot altitude cruise portion of the flight dictated an engine set up with a wide operating range at very low BSFC.

Due to the expected inefficiency of the selected high altitude propeller at take-off and during climb, the Appendix A maximum SHP requirement of 250 was altered to include a 300 SHP take-off and 275 SHP rating for the climb with the final 65000 foot climb rating of 250 SHP. In addition, a mission profile of indicated air speeds was derived from the initial vehicle description by assuming a constant stagnation pressure (q) flight profile. The final flight profile requirements are shown in Figure 5-2 along with the estimated time duration at each of the major flight segments. These power settings and times were then used to evaluate mission fuel burn and the subsequent comparison of each of the studied engine systems.

5.2 Engine Modifications, Control Logic and Subsystem Performance

During the course of the study, four different engines were evaluated for the defined mission. All the engines employed the same bore/stroke and idle/maximum rotational speeds. However, the number of cylinders was varied from 1 through 3 with various turbocompressor/supercharger combinations in order to satisfy mission power requirements. For all the engines studied, the flow and pressure sizing point for the exhaust driven turbocompressor was the 65000 maximum climb (250 SHP) condition.

Each of the engines was configured to meet the mission requirements and then an estimate of mission fuel burn was developed along with the changes in engine system weight to get an approximate figure of merit for final engine selection. The mission fuel burn was computed by running a 15 point engine performance set for the mission and then integrating the total fuel burn by linearly interpolating between the 15 performance points.

Table 5-1 presents the major characteristics of each of the four study engines. Overall mission fuel burn improved as the engine variations moved from Engine A to the Final engine. This improvement was achieved by increasing the maximum compression ratio reached by the engine, by increasing the number of cylinders (resulting in lower engine RPM), and by reducing the flow size of turbine at its 100% Corrected Flow Design point. The reduction in turbocompressor pressure ratio resulted from the decreased charge air density required as the engine displacement was increased. This decrease in turbocompressor work requirement also permitted a reduction in the engine driven supercharger pressure ratio since the turbine pressure drop at low power and altitude was reduced along with the turbocompressor pressure ratio.

Heat exchanger effectiveness values were maintained at a constant 80% throughout the study since their function and performance was unaffected by the variations in engine configuration. A preliminary assessment of the two

TAKE OFF GROSS WEIGHT - LBS	35000
CRUISE/LOITER ALTITUDE - FT	65000
LOITER VELOCITY - KTS	150 - 230
MAX SHP/ENGINE (2 ENGINES)	250
LOITER SHP	44 - 210
RADIUS OF ACTION - N. MILES	2000
LOITER AT ROA - HRS	72

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Figure 5-1 DARPA Vehicle/Mission Requirements

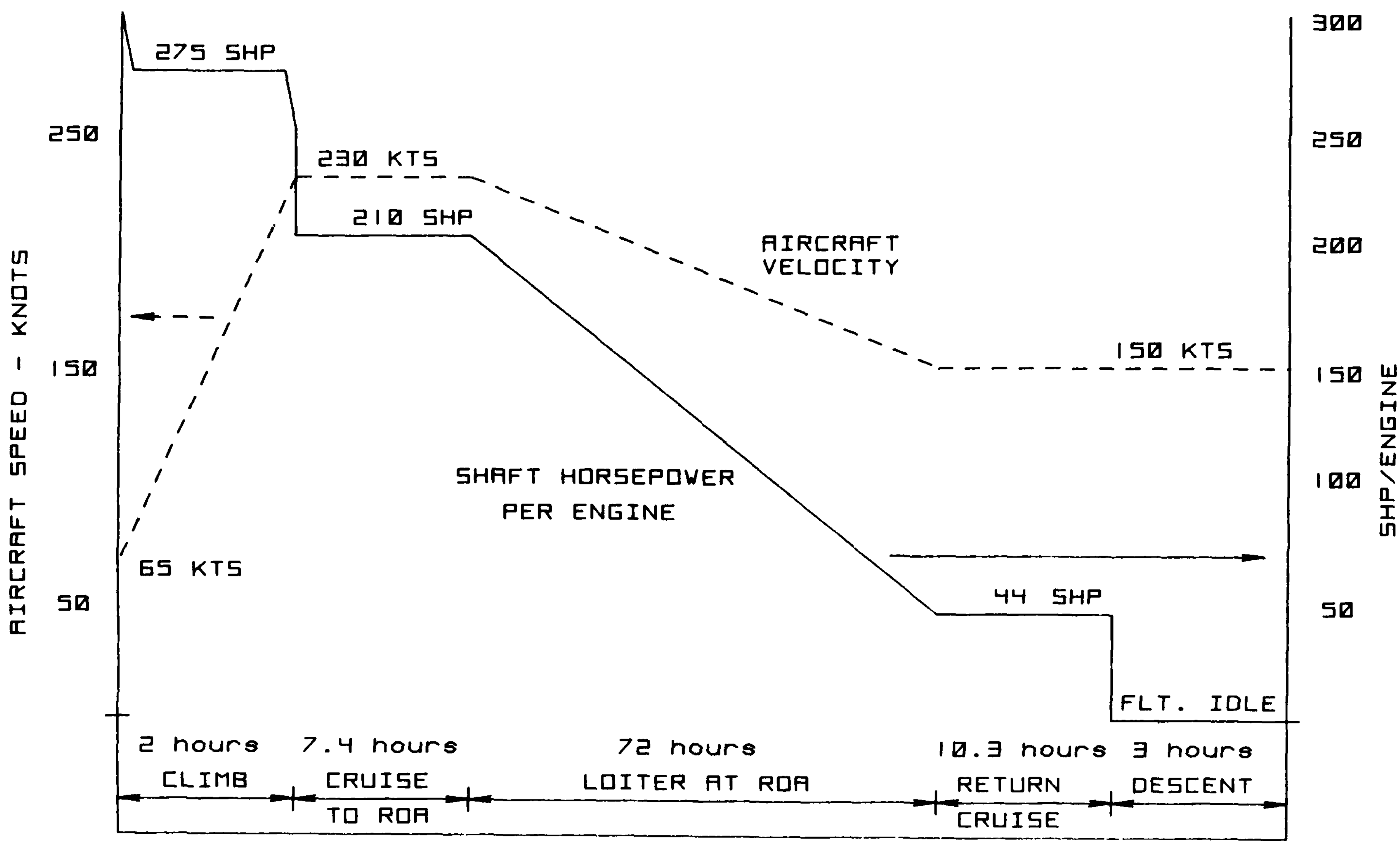
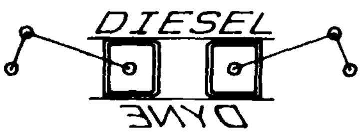


Figure 5-2 Assumed Mission Speed/SHP Profile

Table 5-1 Study Engine Characteristics

	A	B	C	FINAL
NR OF CYLINDERS	1	2	3 →	→
BORE/STROKE - INCHES	3.5/4.85 →	→	→	→
FLTIDLE/MAX RPM	720/3600 →	→	→	→
MAX. COMP. RATIO	60:1	70:1 →	→	80:1
T/COMPRESSOR 100% P/P	24:1	16:1	12:1 →	→
100 % CORR. FLOW - LBS/SEC	10	9	8 →	→
TURBINE 100 % P/P	64:1	9:1 →	→	→
100 % CORR. FLOW - LBS/SEC	.9	1.65	1.6	1.3
S/CHARGER 100 % P/P	1.7:1	1.4:1	1.3:1	1.35:1
100 % CORR. FLOW - LBS/SEC	.5	.6	.7 →	→
I/C EFFECTIVENESS - %	80 →	→	→	→
A/C EFFECTIVENESS - %	80 →	→	→	→



critical heat exchangers (the turbocompressor intercooler and the engine coolant heat exchanger)were performed for the 85000 foot operating conditions and verified the effectiveness choice . The assessment was performed by an application engineer of the Lytron Corporation, Woburn, Massachusetts and the results are included in Appendix B. These results were scaled to the 65000 foot conditions and incorporated as part of the installation description.

A mission fuel burn comparison for the engines defined in Table 5-1 is given in Table 5-2. The total fuel burn decreased from 8658 pounds for Engine A to 6447 pounds for the final study engine. Using the initial Engine A as a base, a change in initial engine plus fuel weight is also shown for each of the engines. As can be seen, the total fuel and engine installed weight decreased as the study progressed. The decrease in fuel burn in going from Engine A (1 cylinder) to Engine B (2 cylinders) amounted to 1544 pounds but only 230 pounds was saved in going from Engine C (3 cylinders) to the final optimized 3 cylinder engine. Since there is a 216 pound engine weight penalty to add an additional cylinder, it was thought that a 4 cylinder engine would not improve the overall fuel plus engine installed weight and was therefore not evaluated.

Table 5-2 also supplies the estimated fuel burn for each major flight segment for each of the study engines. The largest improvement was made in the cruise/loiter portion of the flight and this was due to evolved control logic for the engine and the reduced turbine flow sizing to enhance BSFC for the lower power portions of the cruise/loiter segment. The increase in compression ratio toward the end of the loiter for the later study engines also contributed to the decrease in fuel consumption.

Figure 5-3 displays the changes in Brake Specific Fuel Consumption (BSFC) as the mission proceeds for the final study engine. The majority of the mission was flown at BSFC levels of .250 to .275 pounds of fuel per horsepower hour. The cumulative fuel burn for the mission is also presented. The data reflects standard day conditions for all altitudes.

It was found necessary to control the engine compression ratio as a function of RPM, intake manifold pressure, power level and altitude. Therefore, as the vehicle climbed, the compression ratio schedule began to react to the outside ambient pressure above a critical altitude. This was necessary to avoid excessive combustion chamber pressures and resultant connecting rod bearing loads at lower altitudes. Likewise, the engine driven supercharger was disengaged above a critical altitude when the exhaust turbine was able to extract sufficient gas energy to enable the compressor to provide adequate air pressure and flow. Figure 5-4 describes each of the major engine control parameters and their functional dependence.

Base levels of efficiency were established for the supercharger, compressor, turbine and heat exchangers. A design flow was established (at the 65000 foot climb condition) and then off-design characteristics for the turbocompressor and supercharger were determined by reference performance maps. Scalars were applied to these maps to reflect differences between the base and actual compression components due to size and Reynolds Number effects (altitude). As the component flows and pressures deviated from the design point levels, off-design efficiency levels were computed based on the reference component maps.

Figure 5-5 illustrates the corrected flow as a percent of design flow for the

Table 5-2 Mission Fuel Burn Comparison

(FUEL - LBS)

MISSION SEGMENT	A	B	C	FINAL
T/O AND CLIMB	320.5	327.1	278.0	273.8
CRUISE TO ROA	888.0	896.8	845.2	813.9
LOITER	7106.4	5544.1	5192.2	5012.6
RETURN FROM ROA	334.0	334.2	348.6	334.0
DESCENT	8.5	12.7	12.7	12.7
TOTALS	$\boxed{8658.1}$	$\boxed{7114.9}$	$\boxed{6676.7}$	$\boxed{6447.0}$
Δ ENGINE WEIGHT - LBS	BASE	+216	+432	+432
Δ T/COMPRESSOR - LBS	BASE	-44	-88	-112
TOTALS	8658.1	7286.9	7020.7	6767.0

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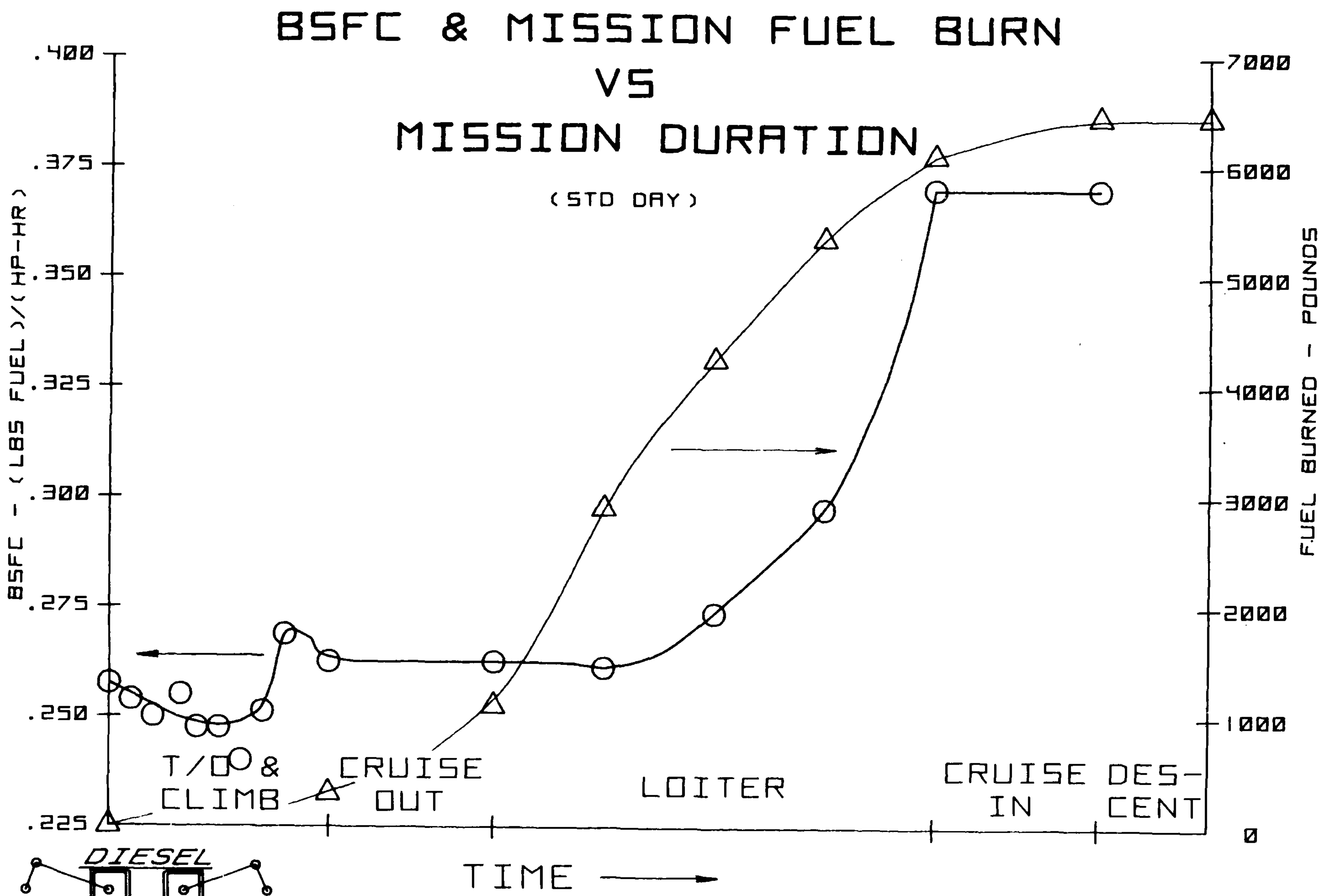

Figure 5-3 Mission BSFC Variation

ALTITUDE ENGINE CONTROL PHILOSOPHY

- COMPRESSION RATIO SET AS:
  F(RPM, M. PRESSURE, ALTITUDE, POWER)

- INJECTOR TIMING SET AS:
  F(RPM, POWER)

- BACK PRESSURE RATIO SET AS:
  F(PURGE FLOW)

- SUPERCHARGER OPERATION SET AS:
  F(ALTITUDE, POWER)

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Figure 5-4 Altitude Engine Control Functions

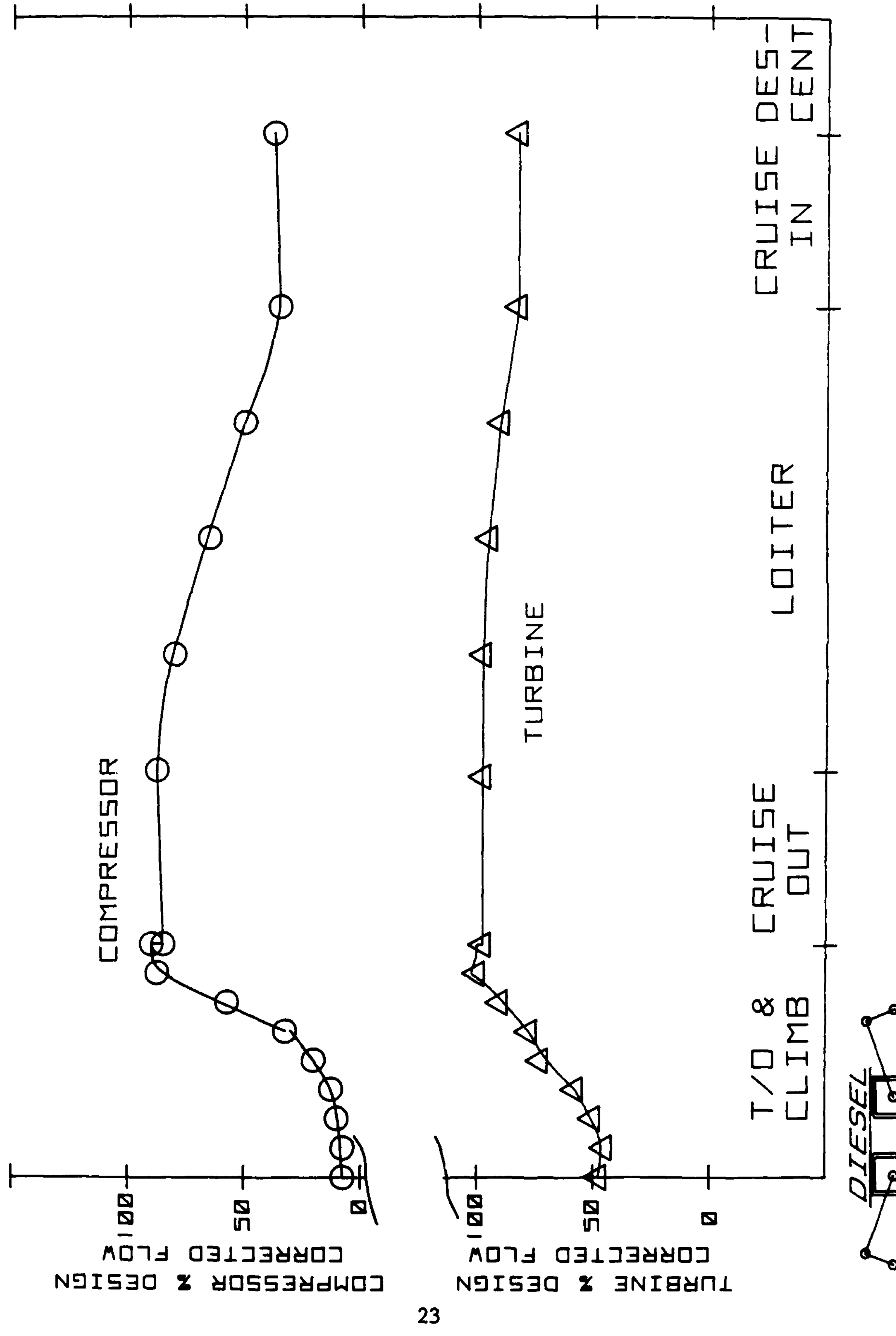

Figure 5-5 Compressor/Turbine Corrected Flow

turbine and compressor as the mission is flown. Scavenge flow control was applied to maintain the compressor and turbine on the most favorable operating lines possible as the engine power varied from the start of cruise to the finish. Figure 5-6 shows the variation in purge (scavenge flow) and the corresponding turbine and compressor adiabatic efficiency levels over the mission.

A variable area exhaust nozzle was used to control the exhaust back pressure and thus the purge flow. By taking the required final exhaust pressure drop through an expanding jet nozzle, supplementary exhaust thrust was also obtained. Figure 5-7 presents the variation of nozzle pressure ratio and nozzle thrust for the mission profile. Towards the end of cruise, it was necessary to take essentially all of the available exhaust system pressure drop through the turbine so that the supplemental thrust dropped almost to zero.

5.3 Engine System and Propeller Assessment

An overall arrangement was developed for the HALE/UAV system that appeared to offer a convenient, yet flexible, installation arrangement. Figure 5.8 illustrates one possible way to install the two engines and auxiliary equipment. Since the heat exchanger function was such an important and difficult function to execute for a vehicle that must fly at such high altitudes but at low recoverable levels of stagnation pressure, a fore and aft engine installation was selected with a large cooling bay connecting the two engines. Initially it was thought that the necessary turbocompressor machinery and variable exhaust nozzle would be one integral unit mounted on the upper outer surface of the cooling bay. However, due to possible icing encounters and foreign object damage, it was decided to install both turbocompressors within the forward portion of the cooling bay just aft of the forward engine. The turbocompressors were laid across the bay perpendicular to the air flow so that any freezing moisture or debris entering the cooling bay inlet would not be able to impact directly into the compressor sections.

Figure 5-9 is a cross section of the turbocompressor and variable exhaust nozzle. To develop the needed pressure ratio, the compressor would require 4 axial stages and 1 centrifugal stage. A two stage axial turbine would be adequate to drive this compressor.

Cooling air is taken into the bay and then decelerated to a design velocity of approximately 60 feet per second so that essentially all of the stagnation pressure available can be utilized for pressure drops through the system. The preliminary evaluation of the 65000 foot heat exchangers indicated that adequate pressure would be available to permit the air to pass through the 4 heat exchangers in series and out through a controllable aft ejector cooling bay flap. This thermostatically controlled flap would control the cooling bay air flow to keep the oil and engine coolant at proper temperature levels.

Both engines utilize parallel and identical cooling circuits that are independent of each other so that a single failure could not cause both engines to stop. Figure 5-10 is a schematic of the heat exchangers and their cooling order. The intercooler and aftercooler are placed ahead of the oil cooler to receive the coolest air and to heat the cooling air so that oil temperatures are maintained at an acceptable value. For the 85000 foot cruise bay arrangement, about 1/3 of the turbocompressor intercooler heat load is taken off after the engine

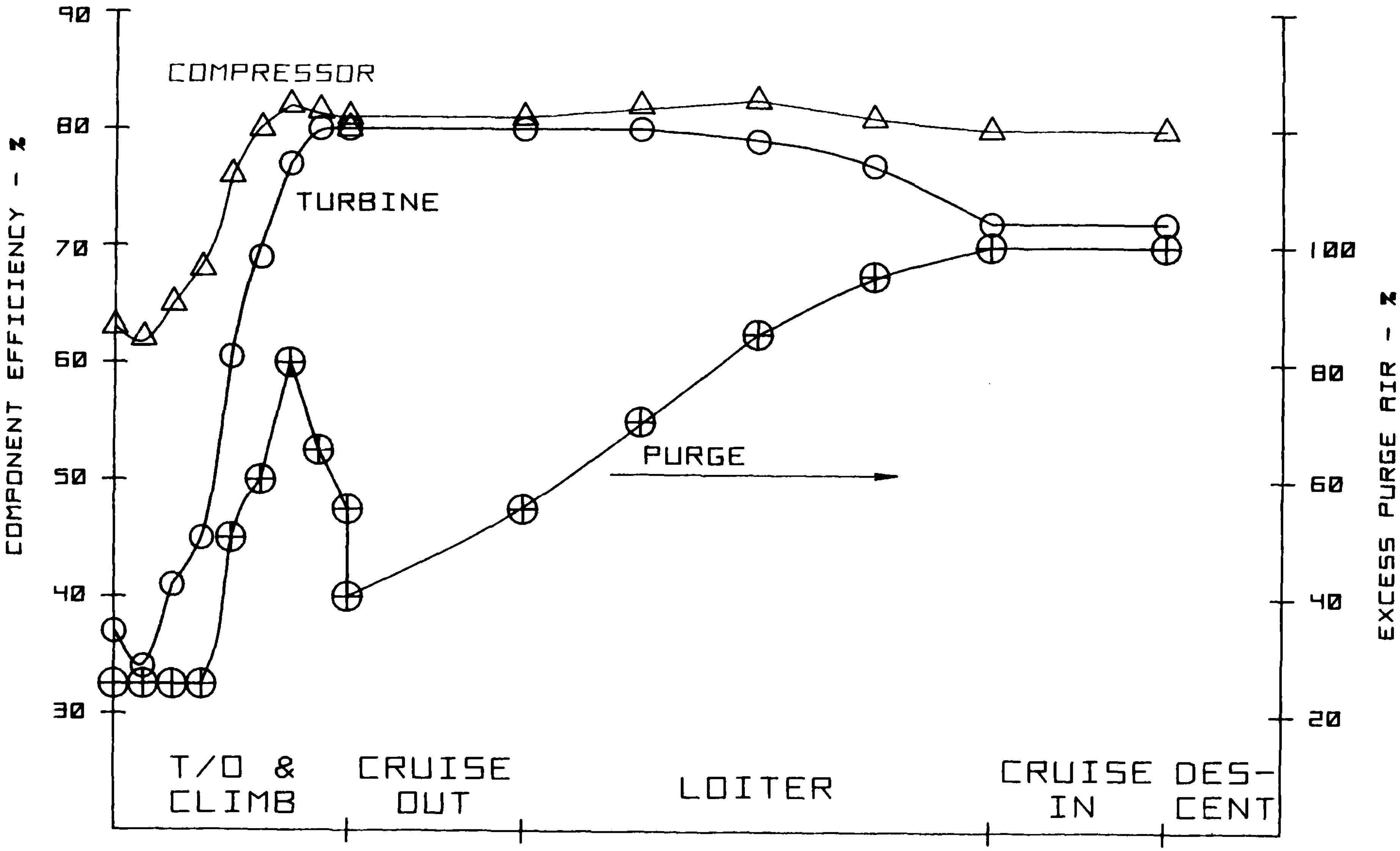

Figure 5-6 Compressor/Turbine Efficiency With Purge Flow

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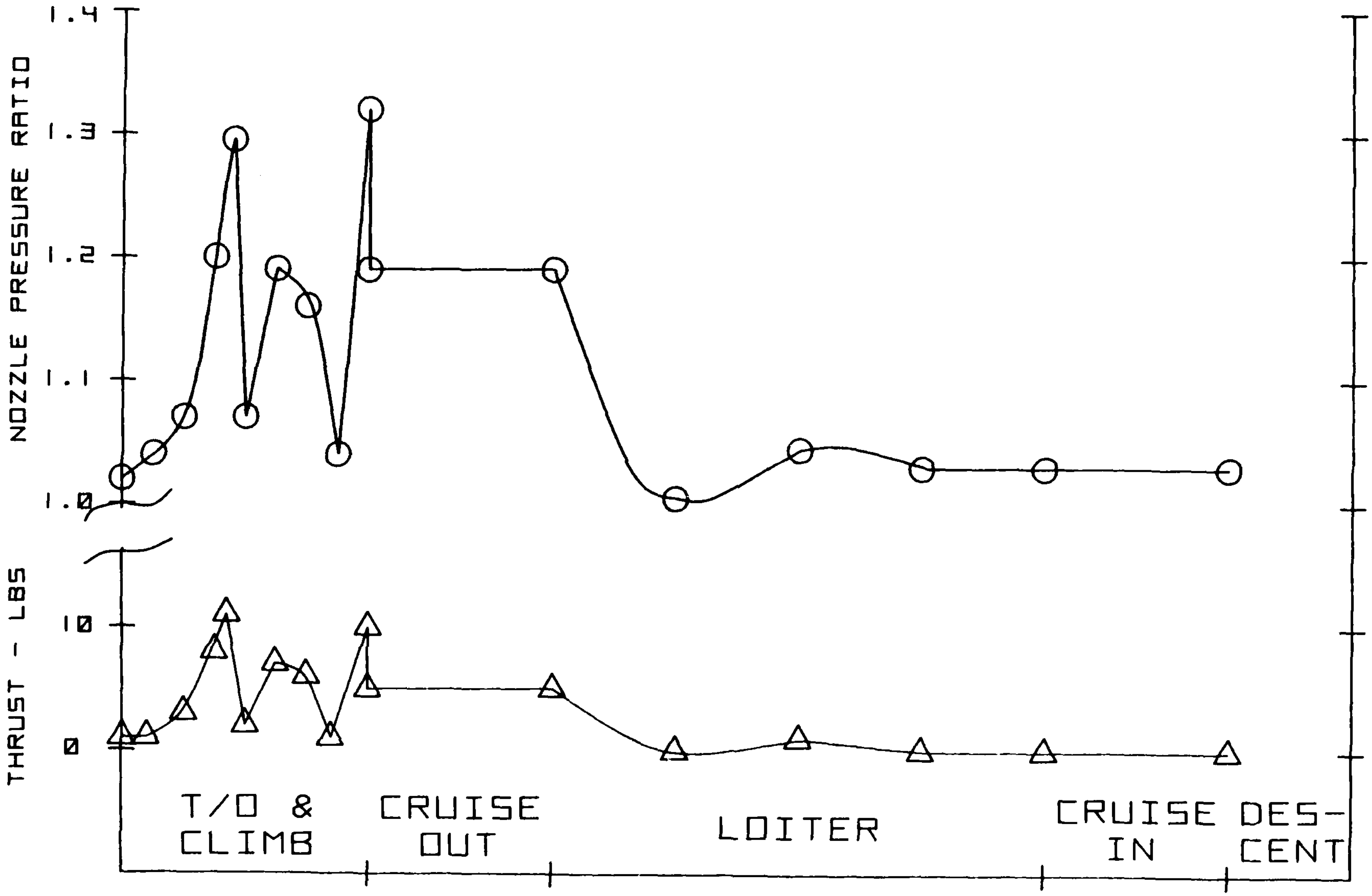

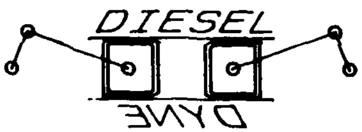

Figure 5-7 Nozzle Pressure Ratio and Thrust

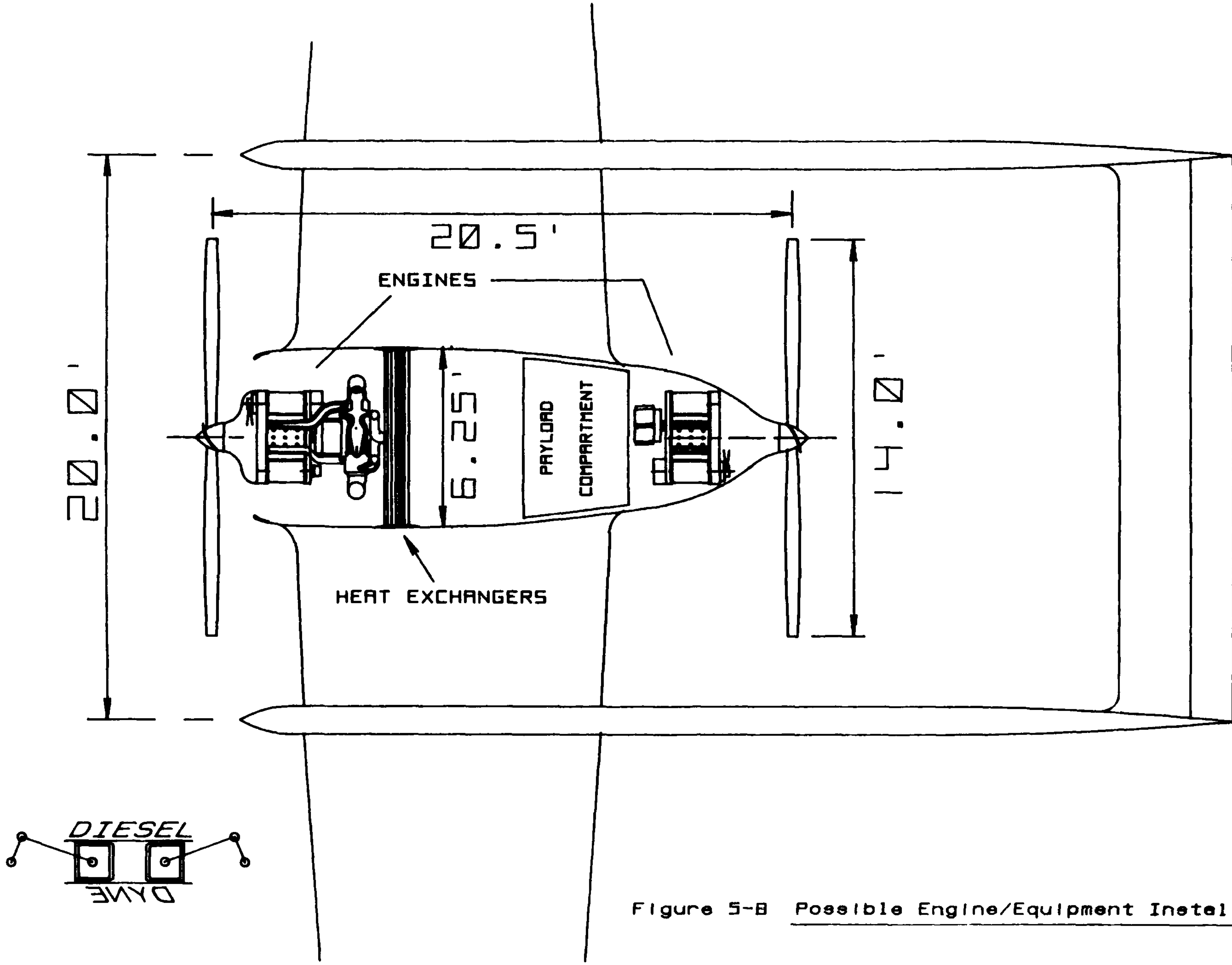

Figure 5-8 Possible Engine/Equipment Installation

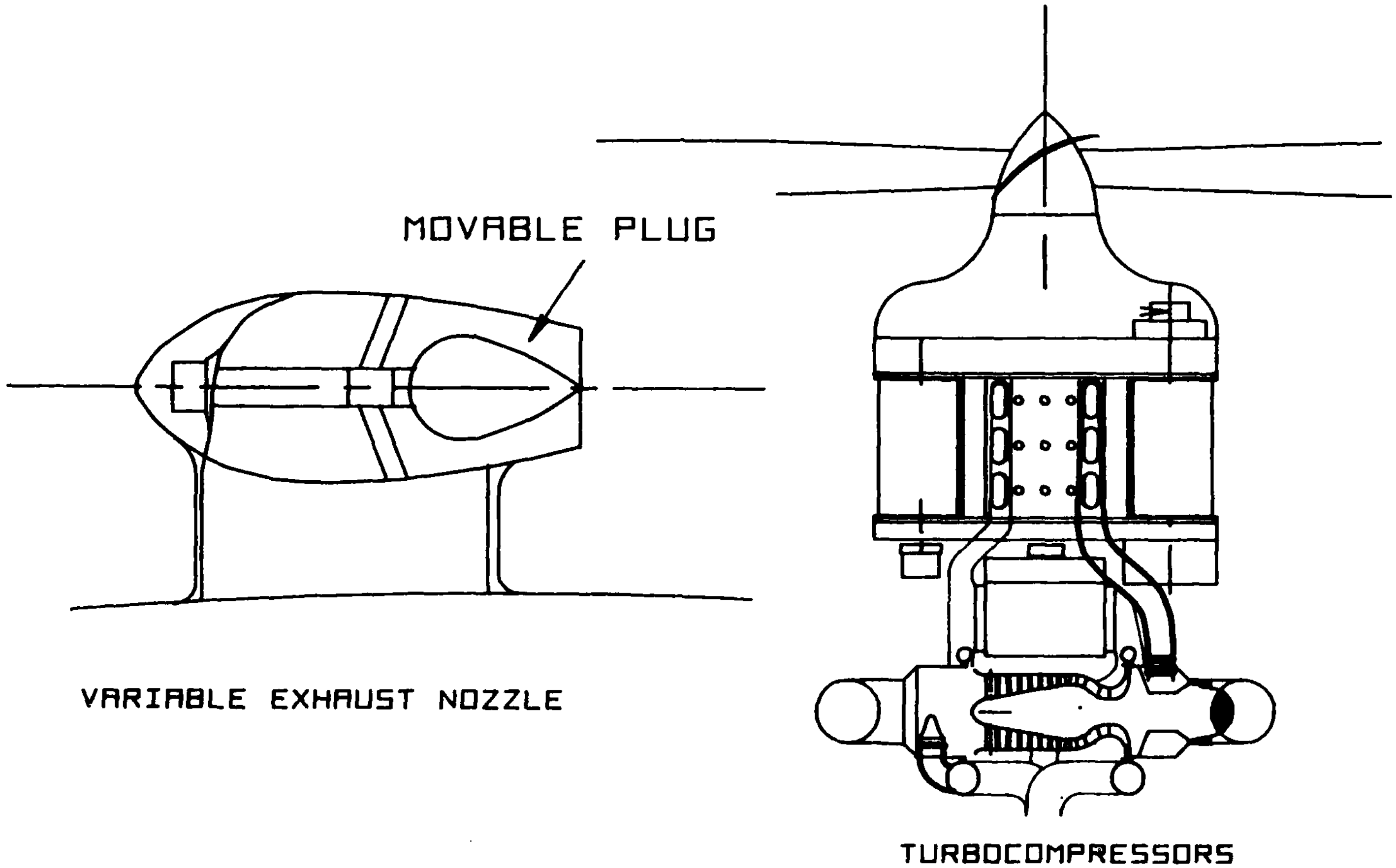

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Figure 5-9 Turbocompressor/Exhaust Nozzle Cross Sections

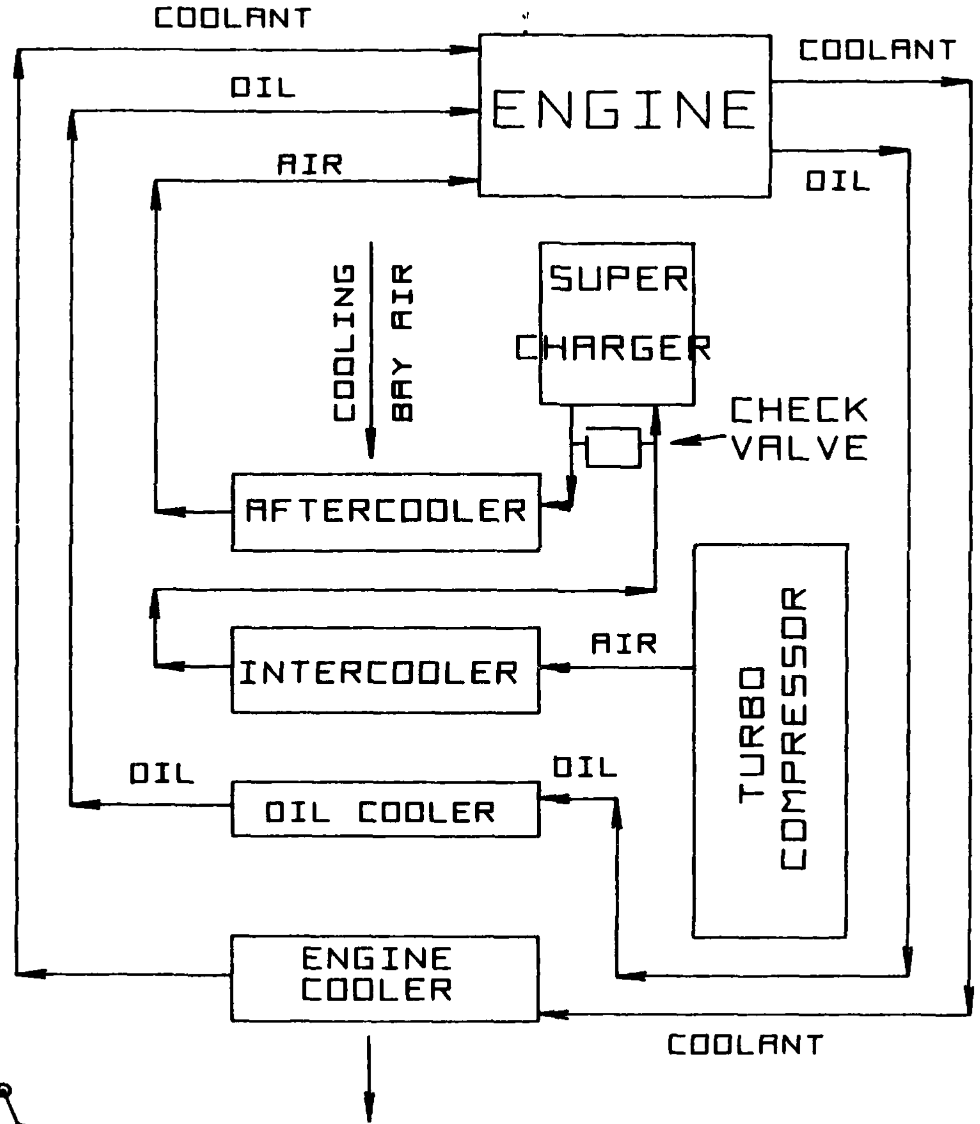

Figure 5-10 Heat Exchanger Circuit Schematic

coolant heat exchanger in a fifth heat exchanger and 2/3 taken off aft of the supercharger aftercooler. This small difference from the 65000 foot cooling bay arrangement is necessary due to the fact that the charge air cooling load is greater for the 85000 foot engine and that the bay cooling air would be too hot to cool the engine coolant if all the charge air cooling was done in front of the engine coolant heat exchanger. Since the 85000 foot cruise charge air enters at temperatures as high as 750 degrees Fahrenheit, there is still a significant temperature gradient (about 500 degrees) between the cooling air and charge air even at the aft end of the heat exchanger stack.

For the 65000 foot installation, the engine cooling bay interior dimensions are approximately 6 feet wide and 5 feet high as shown in Figures 5-11 and 5-12. The engine, manifolding, turbocompressor and heat exchanger mount installation is also shown. Since an 85000 foot vehicle would require a combined cooling bay frontal area of about 72 square feet to satisfy the heat exchanger requirements, the fuselage bay would need to be approximately 9 feet wide by 8 feet high.

After the final 65000 foot cruise engine was selected, a weight estimate was made for the engine and ancillary equipment to determine a "firewall forward weight". Table 5-3 is the weight of all engine system equipment, the propeller and its control. The rear engine has a slightly higher plumbing equipment weight than the front engine since the rear engine's exhaust must be piped forward to the turbocompressor and the compressed air back from the charge air coolers. The total engine system weight for both engines is 2198 pounds.

The propeller performance and weight was scaled and estimated from propeller data found in the Teledyne Ryan report AFWAL-TR-87-3044 dated September, 1987. A 14 foot diameter 4 bladed configuration was selected based on performance map considerations. The aerodynamic design was based on an activity factor of 144 and the overall description of the propeller is given in Table 5-4. The weight was based on a graphite epoxy construction and is somewhat more rigid (and heavier) than a simple scale of the original Teledyne Ryan design due to the additional vibratory forcing present in a fore and aft engine installation.

A propeller map for a similar high altitude application from the reference report was used to select the diameter and loading for the propeller and resulted in a very efficient design throughout the altitude cruise portion of the mission. Table 5-5 shows the estimated adiabatic efficiency and uninstalled thrust for each propeller at the start, mid-point and end of the cruise portion of the flight. With the specified vehicle power and speed characteristics, it was possible to place the propeller in a very favorable portion of the map with operation in the 89 to 90 percent efficiency region. From this data, it would probably not be necessary to use a variable pitch prop at altitude and the required gear reduction from engine RPM (2.32:1) can be accomplished in the main engine timing gear box without an auxiliary reduction gear. This may lead to an exceptionally simple, light and low cost propeller system if the lower altitude portions of the flight are not too far off-design for the propeller. In short, there is an exceptionally good match between the minimum BSFC engine RPM and propeller RPM requirements at altitude.

5.4 System Performance and Sensitivity Analysis

Figure 5-3 displays the expected performance of the AVCD engine at the mission

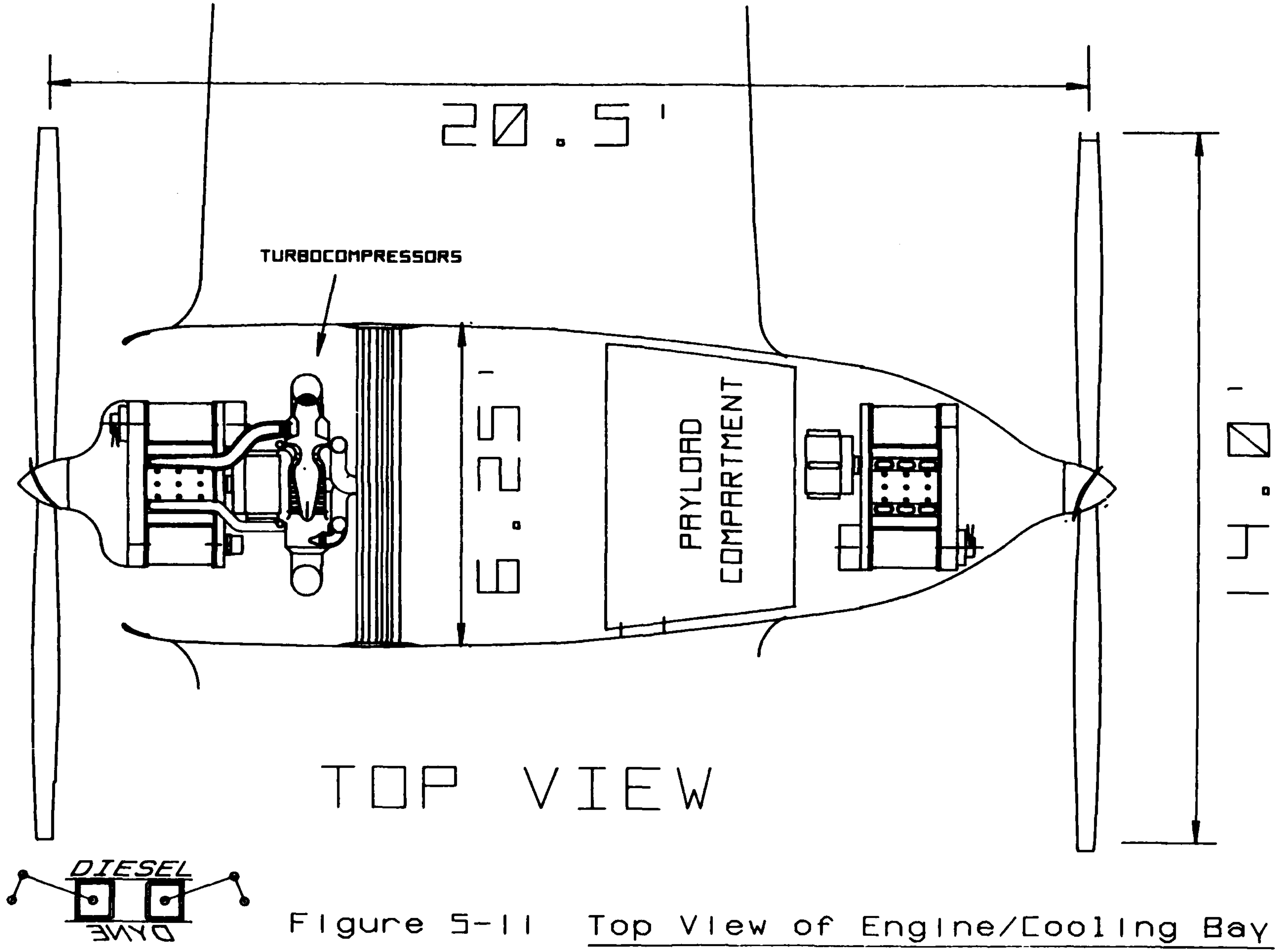

Figure 5-11 Top View of Engine/Cooling Bay

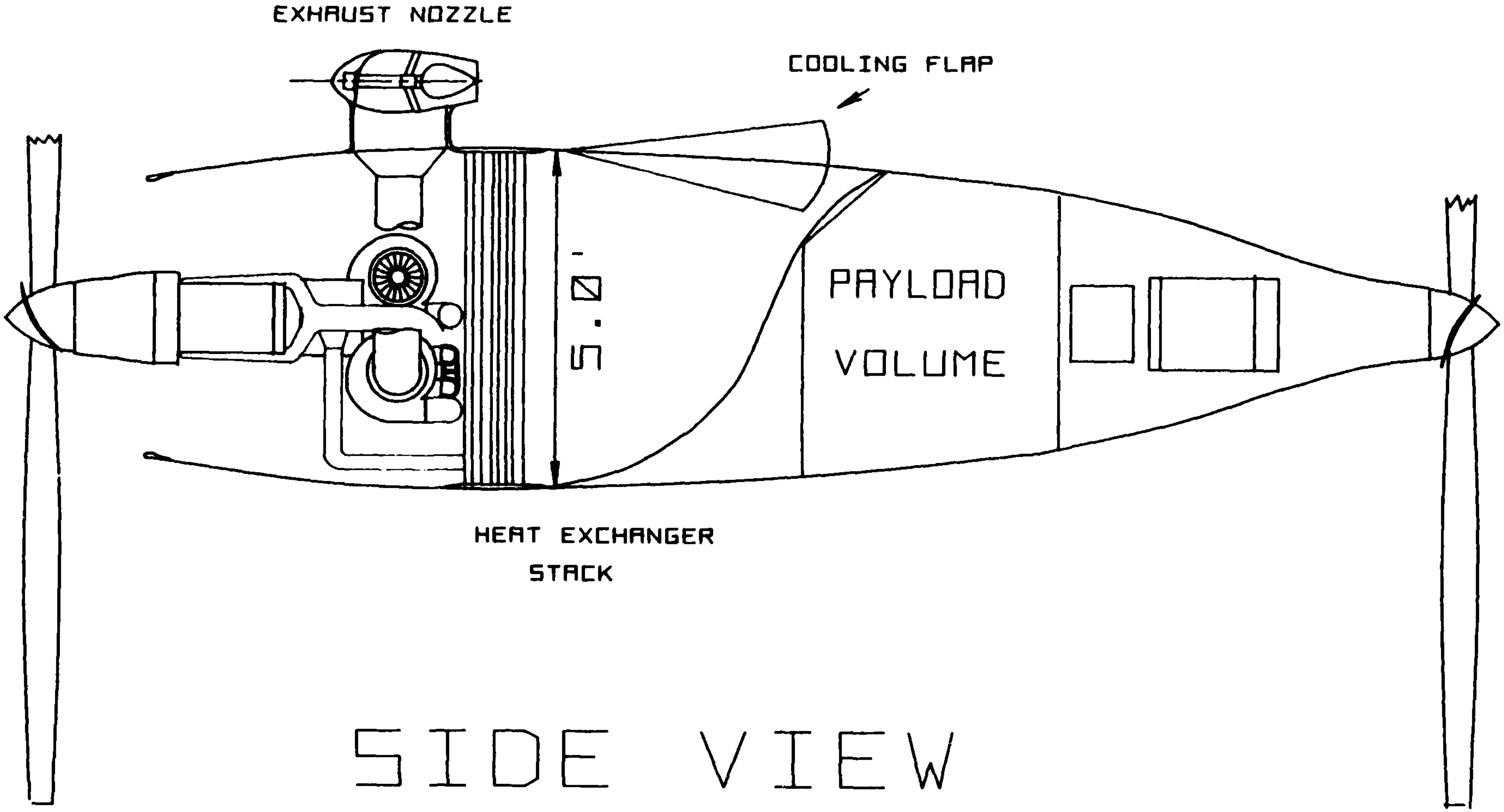

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Figure 5-12 Side View of Engine/Cooling Bay

Table 5-3 Engine System Weight

COMPONENT	FRONT	REAR
DRY ENGINE	599	599
T/COMPRESSOR	159	159
HEAT EXCHANGERS	87	87
TANKS/PLUMBING	36	80
EXHAUST NOZZLE	16	16
FLUIDS	80	80
PROPELLER	100	100
TOTALS	1077	1121

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Table 5-4 Propeller Description

DIAMETER	14 FEET
BLADE NR	4
A. FACTOR	144
PEAK ADIA. EFF.	90+ %
WEIGHT	100 LBS
CONSTRUCT.	GRAPH./EPOXY

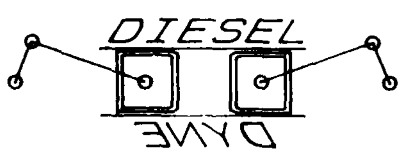

Table 5-5 Propeller Performance

(ENGINE GEAR RATIO - 2.32:1)

PARAM.	CRUISE START	CRUISE MID-POINT	CRUISE END
SHP	210	127	44
RPM	989	860	688
C_p	.179	.164	.111
J	1.68	1.54	1.57
EFF.-%	89.1	88.9	90+
THRUST-LBS	265	194	86

defined power levels throughout the flight. Figure 5-13 shows the expected climb performance of the engines from 10000 feet through 65000 feet for +/- 25 SHP from the base power levels. The variation in RPM for these cases is shown in Figure 5-14. The region of climb where the engine driven supercharger is required is indicated on both these figures.

As part of the study, the effect of small variations in several important parameters on engine performance were evaluated. The effect of a 5% shortfall in heat exchanger effectiveness was determined and is shown on Figure 5-15. The effect was small and ranged from about .35% in thermal efficiency loss at the start of cruise to almost nothing at the end of cruise. It is not anticipated that there is a large risk in achieving the assumed 80% effectiveness levels with state of the art hardware.

Figure 5-16 presents the gain in system thermal efficiency for 5% efficiency improvements for both the compressor and turbine. The individual effects are small for constant engine RPM operation and can vary from about .25% at start of cruise to about .1% at the end of cruise. However, when both components are improved simultaneously, it is possible to slow the engine down approximately 100 RPM and pick up 2.5% thermal efficiency at the start of cruise. Therefore, a development effort to increase the adiabatic efficiency for both the turbine and compressor could have a significant payoff.

Use of turbocompressor bleed air to cool the avionics bay was also examined. A constant altitude bleed of .05 (physical) pounds per second of air was used for the sensitivity study and indicated that very adverse effects on thermal efficiency would result from bleeding this much engine air. Figure 5-17 indicates that at the beginning of cruise, this amount of bleed air would decrease system thermal efficiency by about 4% while a 16% loss could be expected by the end of cruise. (The .05 pound per second bleed represents almost a third of the total engine flow at the end of cruise.) The large efficiency loss suggests that avionics cooling may need to be done by some secondary heat exchanger system such as an air to fluid heat exchanger in the cooling bay or by tanked refrigerant, for instance.

Although excessive bleed air would be quite detrimental to mission fuel burn, expected manifold bleed pressures and temperatures as a function of the mission segment are shown in Figure 5-18. The bleed is taken from the turbocompressor intercooler to obtain more moderate temperatures. Pressures are presented in terms of gage pressure to the ambient conditions and vary from approximately 27 pounds per square inch absolute at take-off to about 4.5 pounds per square inch absolute at the end of cruise.

5.5 85000 Foot Cruise Engine

Figure 5-19 presents a description of an engine system that would perform the same mission with the DARPA defined vehicle but at a cruise/loiter altitude of 85000 feet. The identical engine block is used for both altitudes, but the pre-compression system and heat exchangers are altered considerably. The turbocompressor design pressure ratio must be increased from 12:1 to 24:1 necessitating the addition of two more axial stages. The compressor's design corrected flow is also increased from 8 pounds per second to 20 pounds per second. The turbine corrected flow size is decreased from 1.3 pounds per second to 1.1 pounds per second to accommodate the required turbine design pressure

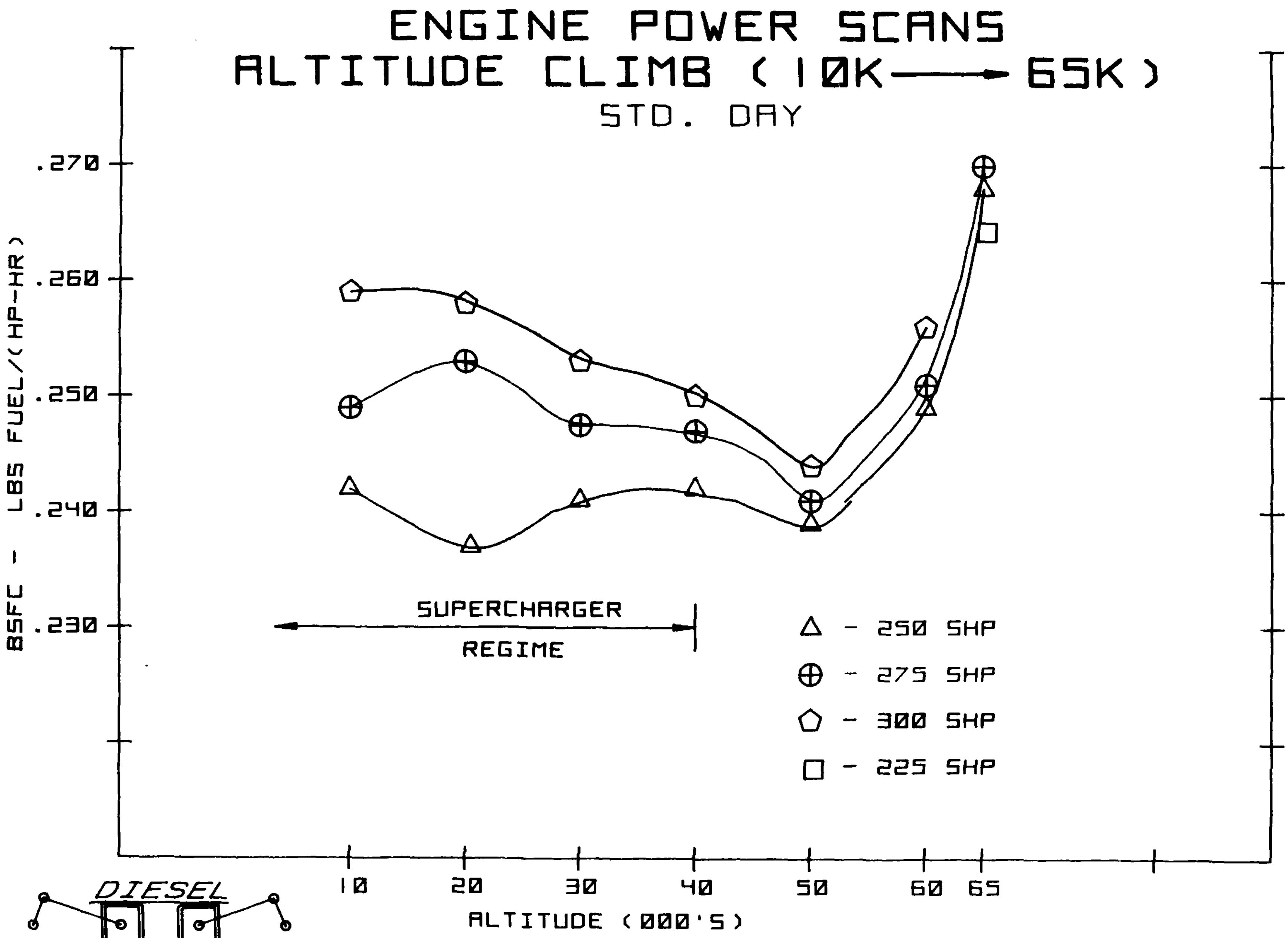

Figure 5-13 Climb Performance Excursions

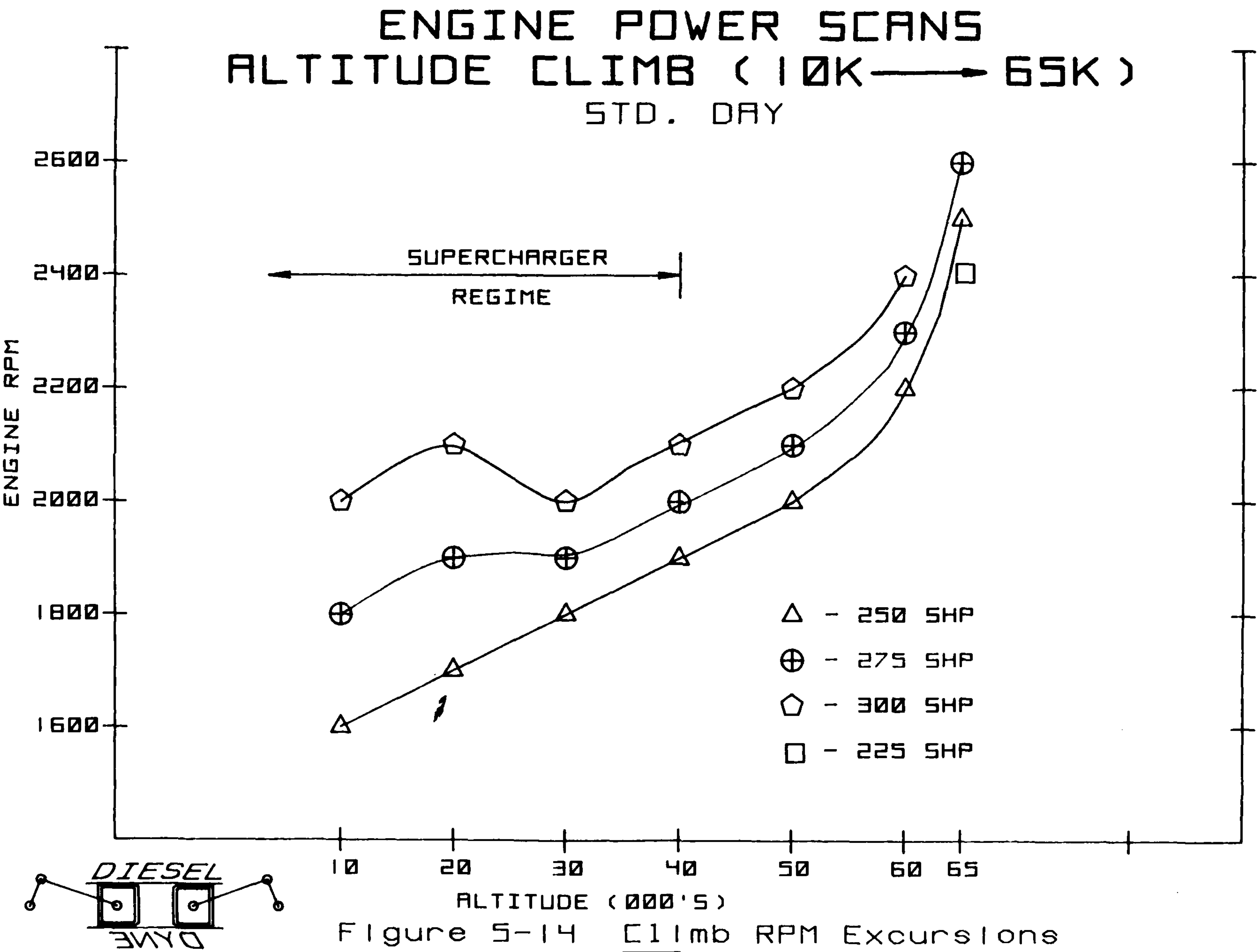

Figure 5-14 Climb RPM Excursions

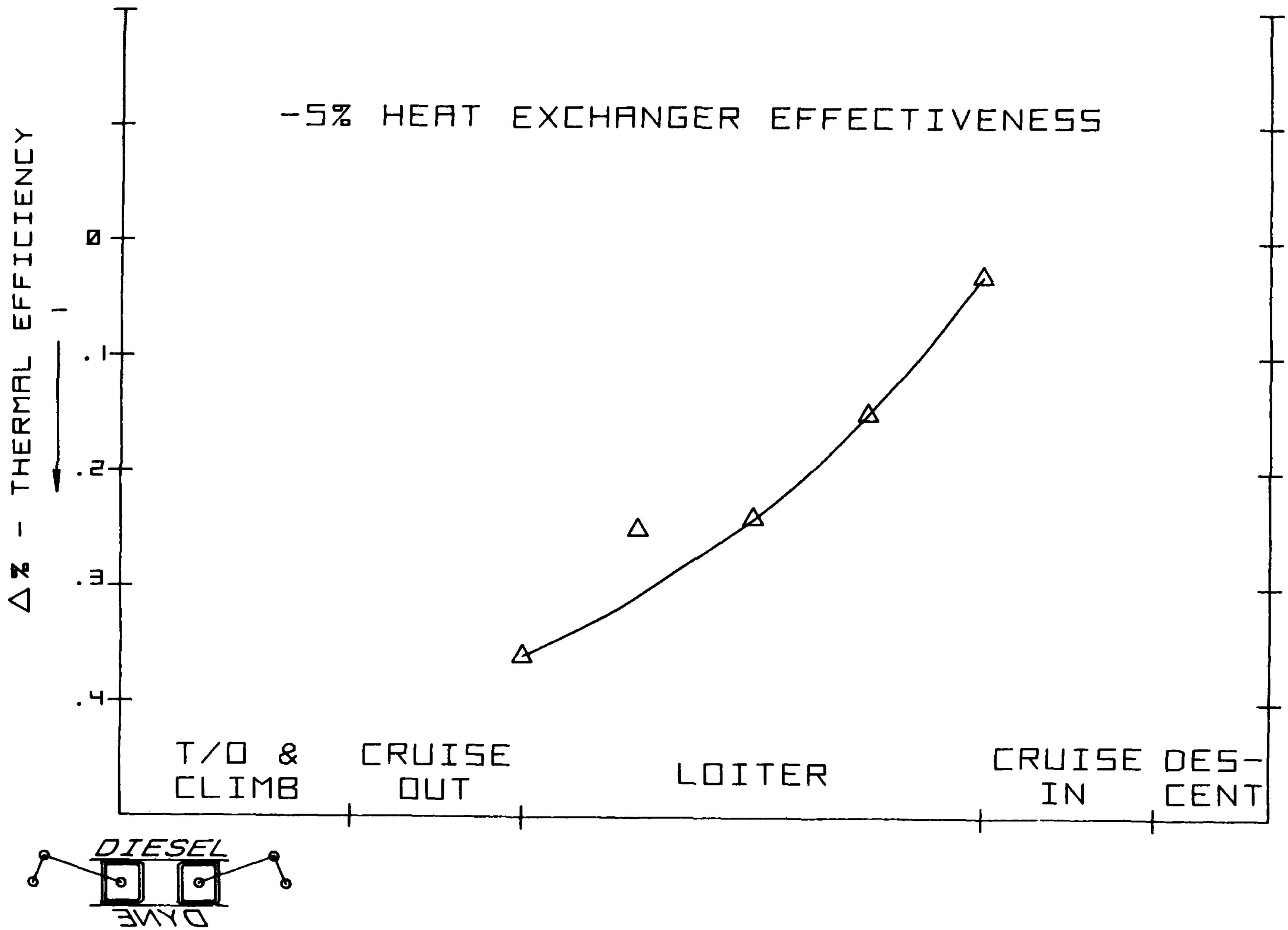

Figure 5-15 Performance Sensitivity to Exchanger Effectiveness

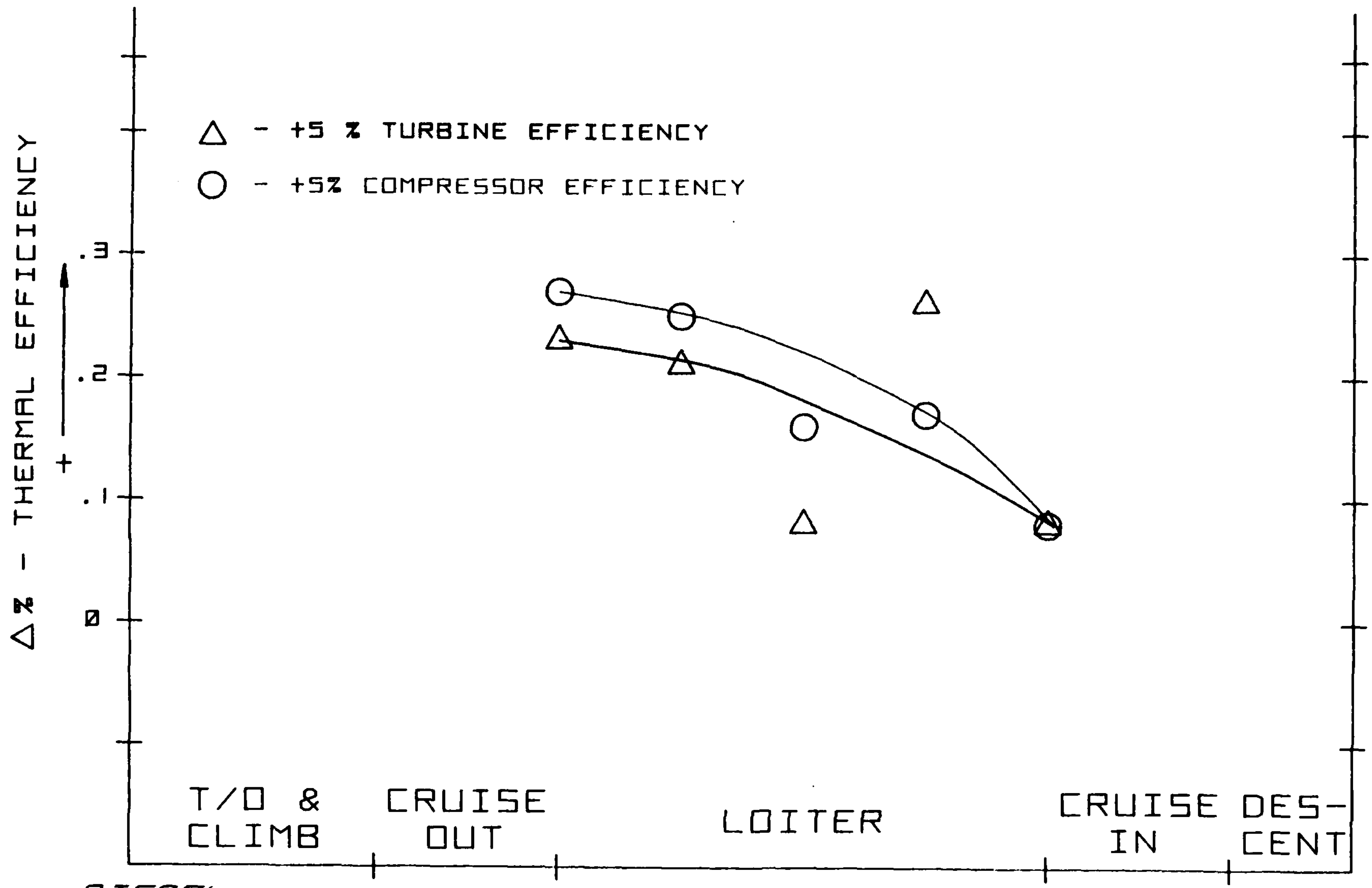

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Figure 5-16 Performance Sensitivity to Compressor/Turbine Efficiency

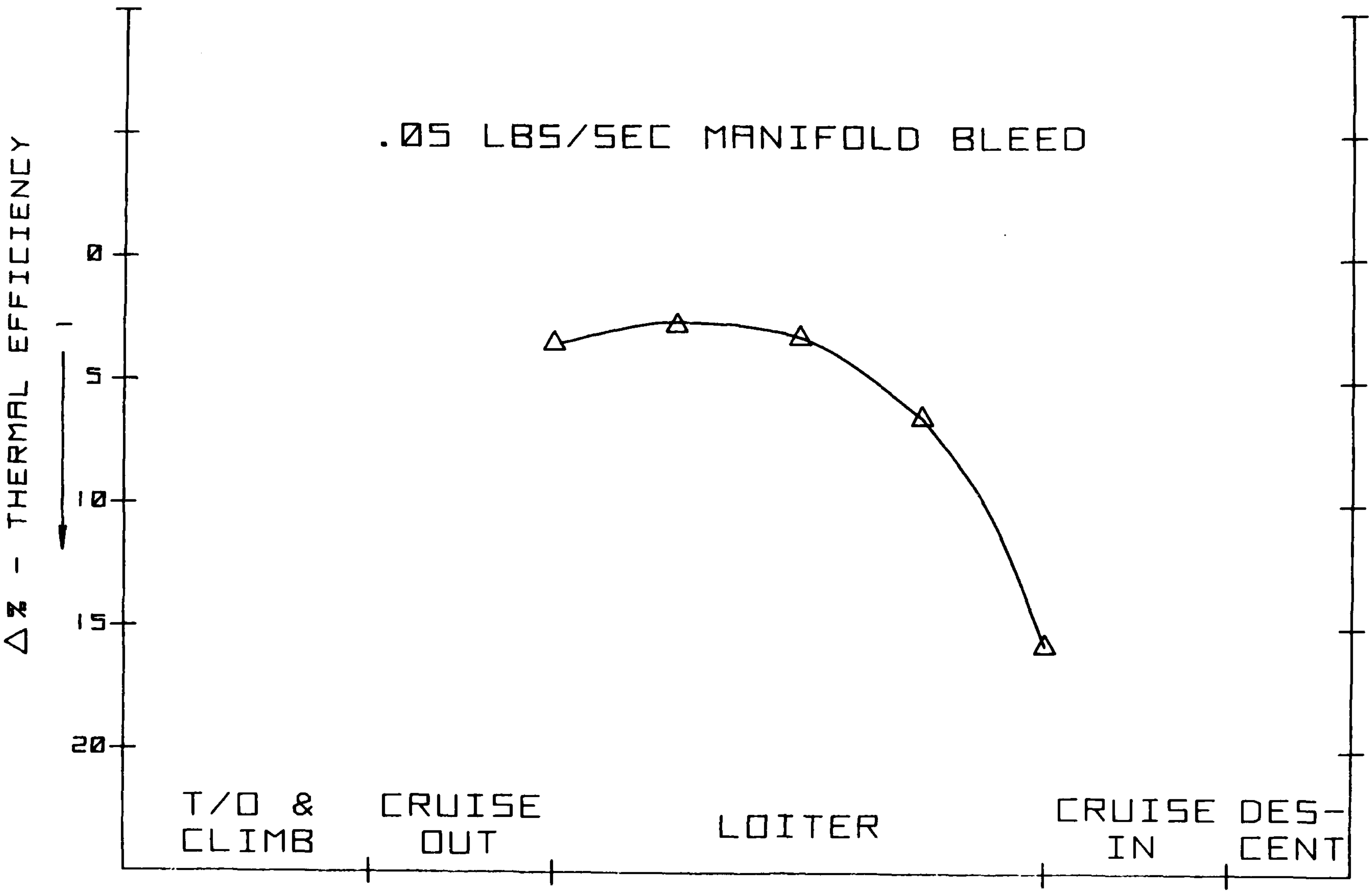

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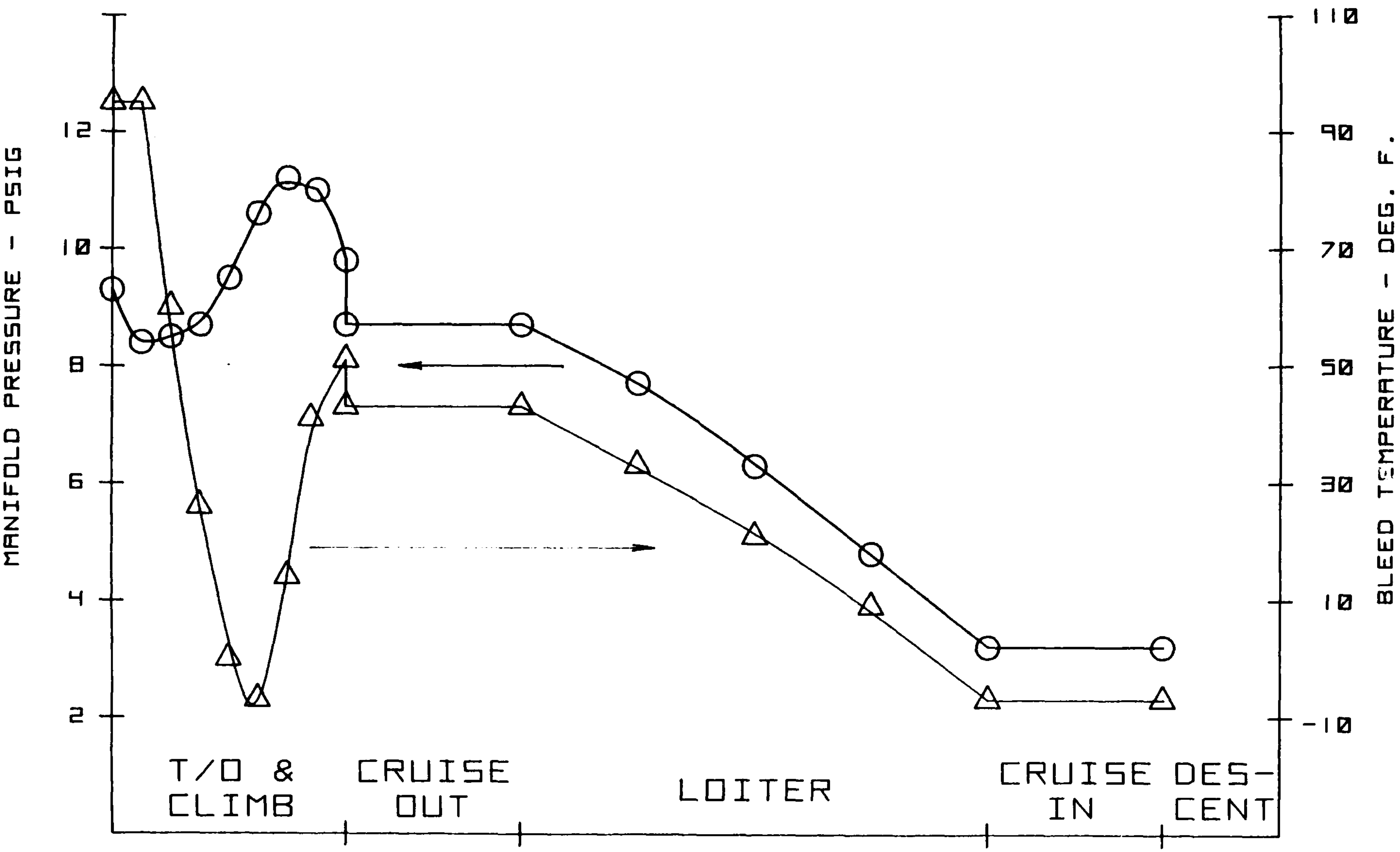
Figure 5-17 Performance Sensitivity to Engine Bleed Air



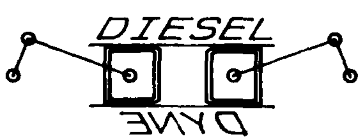


Figure 5-1B Manifold Air Temperature and Pressure

NR OF CYLINDERS	3
BORE/STROKE - INCHES	3.5/4.85
FLT IDLE/MAX RPM	720/3600
MAX COMP. RATIO	80:1
T/COMPRESSOR 100% P/P	24:1
FLOW SIZE - LBS/SEC CORR.	20
TURBINE 100% P/P	27:1
FLOW SIZE - LBS/SEC CORR.	1.1
S/CHARGER 100% P/P	1.7:1
FLOW SIZE - LBS/SEC CORR.	1.5
T/COMPRESSOR STAGING	6 AX/1 CF
TURBINE STAGING	3 AX
H/X EFFECTIVENESS - %	80

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Figure 5-19 85000 Foot Cruise Engine Description drop increase from 9:1 to 27:1. An additional axial stage must be added to the turbine for a total of 3 axial stages. The Roots-type blower pressure ratio must also be increased from 1.35:1 to 1.7:1 due to the increased turbine pressure drop. As mentioned previously, the heat exchanger frontal area for each engine is increased from 15 square feet to 36 square feet to handle the increased charge air heat transfer in the less dense air available at 85000 feet.

A few performance spot points for the 85000 foot engine are presented in Table 5-6 and indicate that the 85000 foot BSFC levels are essentially identical to the 65000 foot engine BSFC values. The 85000 foot vehicle Mach Numbers were developed by holding the 65000 vehicle cruise and climb stagnation pressures (q) so that the wing's coefficient of lift values would be identical. Therefore, it would be expected that the DARPA defined mission (with a lighter vehicle) could be carried out at 85000 feet for essentially the same mission fuel burn, but the larger turbocompressor and propeller would cause the engine system to be heavier.

The propeller for the 85000 foot system would be approximately 20 feet in diameter and have 4 blades. It is also likely that the required engine to propeller overall gear reduction ratio would require an additional stage of transmission gearing in addition to the gearing of the primary engine timing gearset or an additional cylinder to permit the engine RPM to be lowered depending on the alternative producing the lightest engine system.

Table 5-6 65000/85000 Foot Engine Performance

	(SFC)	
	65K	85K
SLTO - 300SHP	.265	.310
MAX CLIMB, 40K	.243	.240
MAX CLIMB, TOP	.279	.282

APPENDIX A

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
1400 WILSON BOULEVARD
ARLINGTON, VA 22209-2308

Mr. Richard P. Johnston
Diesel Dyne Corporation
3044 Middleboro Road
Morrow, OH 45152

Dear Mr. Johnston:

Your Advanced Variable Cycle Diesel Engine Study requires the Government to provide an additional definition of propulsion system requirements for your baseline propulsion system sizing. DARPA's basic interest is in High Altitude Long Endurance (HALE)/Unmanned Air Vehicle (UAV) systems. Many studies have been conducted by the Services which size HALE systems to meet existing needs. Unfortunately, the studies result in propulsion sizes that range from 100HP to 600HP with no consensus on mission requirements.

As a starting point for your study the following nominal characteristics are provided:

Takeoff gross weight	=	35,000 lbs
Cruise and loiter altitude	=	65,000ft
Loiter velocity	=	150kts to 230 kts
Max shaft HP/Engine (2 engines)	=	250 HP (Sized for takeoff & climb)
Loiter shaft HP (approx)	=	210-44HP
Radius of Action (ROA)	=	2000 N. Mi (approx. 20 hrs.)
Loiter at ROA	=	3 days (72 hrs.)

Turbo charged to sea level manifold pressure
Diesel engine
Low BSFC is primary concern--not system weight

This is about as detailed as I can get for the moment, but it should be adequate to initiate your study.

Sincerely,

Ronald D. Murphy
Program Manager, Aerospace and
Strategic Technology Office

APPENDIX B

DieselDyne Corporation
3044 Middleboro Road
Morrow, Ohio 45152

December 8, 1988

Director
Defense Advanced Research Projects Agency
Attn: Mr. Ronald D. Murphy
1400 Wilson Boulevard
Arlington, Virginia 22209-2308

Mr. Murphy:

Enclosed is the Quarterly Status Letter report required on Contract DAAH01-88-C-0660 as item A001 of the contract CDRL. The report summarizes the progress and the major results of the study conducted from August 11 through November 10, 1988.

CERTIFICATION

The contractor, DieselDyne Corporation, hereby certifies that to the best of its knowledge and belief, the technical data delivered herewith under Contract DAAH01-88-C-0660 is complete, accurate, and complies with all requirements of the contract.

December 8, 1988

____
Richard P. Johnston, Pres.

Quarterly Status Report

A Study of an Advanced Variable Cycle Diesel Engine for Use in a Remotely Piloted Vehicle

Contract DAAH01-88-C-0660

by the
DieselDyne Corporation

Background

The current contract began August 11, 1988 and is scheduled to be complete on February 28th, 1989. The purpose of the study was to examine an Advanced Variable Cycle Diesel (AVCD) as applied to a Remotely Piloted Vehicle (RPV) to determine the AVCD's operating characteristics, configuration, engine control philosophy, performance, installation and weight. There were four major technical tasks proposed for the study as follows:

I. Select Operational Requirements and Engine Size
II. Determine Engine Modifications, Control Logic and Subsystem Component Performance
III. Assess Total System - Propeller, Subsystem Sizing, Firewall Forward Weights and Installation
IV. Complete Engine Performance Characterization and Develop Performance Derivatives

The following status report covers the first three months of technical effort through November 10, 1989. During this period of time, Tasks I and II have been completed and Task III is approximately 40% complete. No unexpected technical problems have been encountered and the study is currently on schedule.

Discussion

The initial Task was to develop the operational requirements of the RPV and to size the engines to satisfy these requirements. Mr. Murphy, the program manager for this study, provided the original vehicle/engine requirements (shown in Appendix A) and from these, an assumed mission speed/time and shaft horsepower profile was generated as shown in Figure 1. This mission was applied to each of the study engines to develop a fuel burned figure of merit. Figure 2 illustrates the study aircraft's assumed engine installation and ancillary equipment arrangement. A fore and aft engine arrangement was selected because it was thought that some swirl energy recovery from the forward prop might be possible by the aft propeller.

The overall engine system studied is shown in the Figure 3 schematic and consists of an AVCD engine with an exhaust driven turbocompressor, an intercooler, an engine driven supercharger that discharges into an aftercooler and then into the engine. The engine itself direct drives the propeller. A cross section of the engine studied is given in Figure 4. Although the study engines were varied in displacement to reach a satisfactory size, this was done by varying the number of cylinders rather than the cross sectional dimensions.

The turbocompressor was assumed to be of the type shown in Figure 5 with forward axial stages delivering air to a single stage centrifugal compressor. This compressor format has been used successfully in the aircraft turbine field for compressors of the size and pressure ratio required for this study. Multi-stage axial turbines were used for all of the turbocompressors studied.

A variable area jet nozzle (Figure 6) was used to provide flow control for the engine and through the turbine and compressor while recovering any unused pressure work as jet thrust. Although the original system schematic (Figure 3) showed the turbocompressor and variable exhaust nozzle as an integrated unit, installation considerations indicated that a better arrangement might result if the nozzle alone was exposed to the ambient airstream. Both turbocompressors were then mounted behind the forward engine in a stagnation recovery cooling bay.

Control logic found to be necessary for proper AVCD engine operation in this application is shown in Figure 7. Although the functions required to properly adjust the compression ratio were similar to those used on ground engines, their values and range were modified considerably and it was found that altitude compensation had to be applied in addition. Operation of the supercharger was likewise altered by the addition of an altitude control function.

During the course of the first three months of the study effort, three separate engine systems were examined and compared on the basis of the benchmark mission. Figure 8 shows the differences (and similarities) between each of the systems. Based on the mission shaft horsepower requirements, the initial engine was a single cylinder design. Although it satisfied the vehicle requirements, the engine ran at near maximum rated speed and was not as fuel efficient as had been hoped. The effective displacement of the single cylinder engine was approximately 76 cubic inches and since cylinder size was not varied, the "B" engine displaced 152 cubic inches and the "C" engine displaced 228 cubic inches.

The use of such a small displacement on the "A" engine also put heavy requirements on the turbocompressor's compression and turbine sections and increased the pressure ratio requirements of the engine-driven supercharger. All these system requirements impacted the fuel consumption of the RPV equipped with the "A" engine and therefore it was decided to increase displacement, slow the engine down and to decrease the pre-compression system requirements. It was also found that the maximum compression ratio of the engine (at altitude) also had to be raised to maintain thermodynamic parameter efficiency levels. The series of studies that followed resulted in the "C" engine as the current selection.

Figure 9 is a top view of the "C" engine and illustrates the crankshaft spacing, overall width and overall length. The supercharger for the "C" engine is not shown as it will be a detached belt driven Roots-type blower. A comparison of fuel burns for each of the engines examined is shown in Figure 10. The weight of fuel for each of the major mission segments for the vehicle is given and it can be seen that the mission fuel burned decreased significantly from engine "A" to "B" to "C". In going to the larger, slower engine configurations, nearly a ton of fuel was saved notwithstanding that the "C" engine also was required to supply a 10KW electrical load (total of 20KW for the vehicle) that was not supplied by the "A" or "B" engines.

The weight impact on the RPV TOGW of the fuel savings coupled with the increased engine system weights is also presented in Figure 10 below the fuel burned totals. Using the initial single cylinder engine installation as a base, the TOGW savings is approximately 1600 pounds due to the increase in engine weight with some offset due to the de-staging of the turbocompressor. It can also be seen that the fuel burn plus engine weight deltas are rapidly approaching an asymptote indicating that a four cylinder engine might begin to increase the TOGW.

Figure 11 illustrates the Brake Specific Fuel Consumption (BSFC) and fuel burned of the "C" engine as the mission proceeds while Figure 12 shows the changes in engine RPM and compression ratio during the same periods. The compression ratio varied from the high 20's at take-off to the mid-60's during the high altitude loiter portion of the mission.

Since an RPV of this type might be required to dissipate a significant amount of heat from the equipment bays, manifold bleed pressure and temperatures were determined during the mission and are given in Figure 13. Pressure is expressed in terms of gage pressure over the outside ambient conditions and varies from a high of about 11 during climb to as low as 3.5 during the last portion of the loiter when engine horsepower is at a minimum. Air temperatures are in Fahrenheit and are for the air as it leaves the aftercooler. Warmer air could be obtained by tapping the air after the intercooler or by mixing uncooled air directly from the turbocompressor.

Figures 14 and 15 depict the corrected flow through the compressor and turbine as the mission proceeds and illustrate the use of the variable engine purge (controlled by the variable exhaust nozzle) to maintain appropriate flows (and component efficiencies) throughout the widely varying ambient flight and engine conditions. The nozzle pressure ratio required to exert this control is shown in Figure 16 and the residual thrust available is also given. As can be seen, significant thrust is only available during late climb and the early portions of the cruise and loiter when engine horsepower is relatively high.

Figure 17 displays the maximum compression pressures reached in the combustion chamber at the instant of fuel ignition as well as the maximum combustion pressures reached during the burning of the fuel for the various segments of the mission. Likewise, the connecting rod loads at the wrist pin and crankshaft for the mission are also represented. Use of the variable compression ratio and variable backpressure control permitted the loads to be held at relatively constant levels for similar power levels even though the aircraft was climbing from sea level to 65000 feet. At altitude, while intake manifold pressures decreased by over 300 per cent, compression pressures varied by only about half as much. This ability of the AVCD engine to control and maintain internal cycle conditions through large swings in ambient conditions, speed and power levels permits extremely good part power and off-design performance.

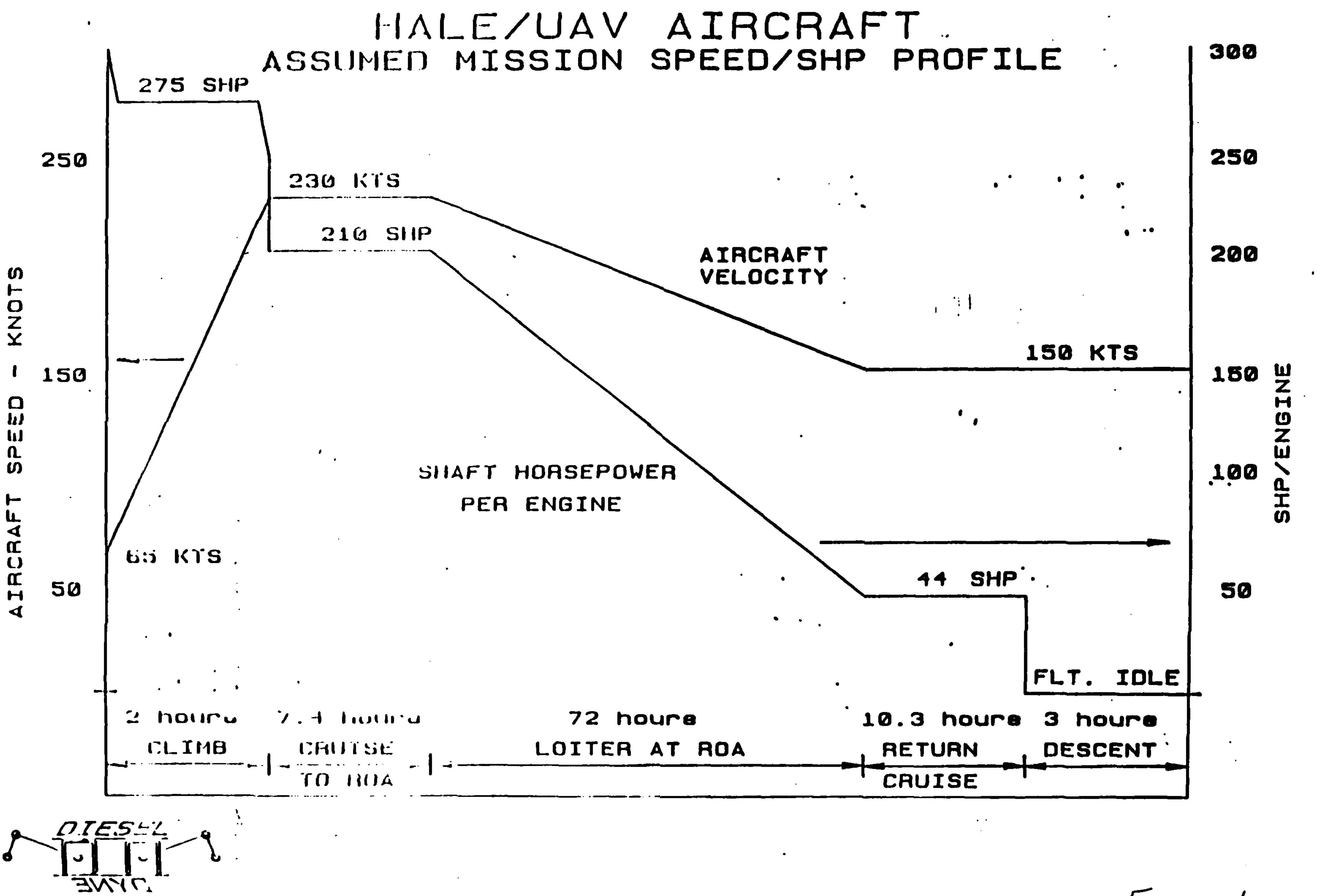
As part of the TASK III effort, a "firewall forward" weight estimate is being developed for the completely installed engine. Thus far, a preliminary weight estimate for the engine and its ancillary equipment has been completed and is given in Figure 18. This weight also includes the weight of the engine driven Roots supercharger.

Some characteristics for an engine suitable for the RPV mission but at an 85000 foot cruise/loiter altitude have been determined and are shown in Figure 19. The "C" engine configuration has been retained, but the turbocompressor pressure ratio has been raised to 24:1 and the supercharger pressure ratio to 1.7:1. One additional turbine stage is required along with two additional compressor stages to provide this level of pre-compression. The flow size of the compressor is more than double that of the 65000 foot engine. However, some spot point BSFC data computed and compared with the "C" engine values in Figure 20 indicate that the 85000 foot engine fuel consumption is essentially the same. Therefore, an AVCD engine and RPV vehicle could be configured to carry out the same mission at 85000 feet altitude with the same fuel burn.

The major advantage of an AVCD engine over a conventional non-variable cycle engine is the reduced amount of pre-compression pressure ratio and machinery needed for the same power output. In Figure 21, a comparison of the 85000 foot engine system with a comparable fixed cycle engine from another study is made and illustrates the reduced pre-compression needed. For the fixed cycle engine, 50% more pre-compression is required, one addition compressor, three additional turbines, a turbo-compounding system, much higher levels of component efficiency and no exhaust thrust recovery is made. The ability of the AVCD engine to vary its compression ratio to maintain good combustion chamber conditions relieves the pre-compression system of the need to maintain engine near sea level intake conditions.

Conclusions

The study of an AVCD engine applied to an RPV has progressed as planned and is on schedule. TASKS I and II are complete and TASK III is approximately 40% complete. Methods of matching the turbocompressor components to the engines needs have been developed and information about the operating characteristics of a suitable 65000 foot engine is being generated. Control logic has been developed with a few "tweaks" left for final mission assessment. Computational methods and sub-routines are in place and operational to permit the completion of TASKS III and IV. Expenditure rates are tracking the expected schedules closely and it is anticipated that the study will be completed within the initial proposed levels of spending and on schedule.



HALE/UAV AIRCRAFT
ASSUMED MISSION SPEED/SHP PROFILE
275 SHP
230 KTS
210 SHP
AIRCRAFT
VELOCITY
150 KTS
SHAFT HORSEPOWER
PER ENGINE
65 KTS
44 SHP
FLT. IDLE
2 hours
CLIMB
7.4 hours
CRUISE
TO ROA
72 hours
LOITER AT ROA
10.3 hours
RETURN
CRUISE
3 hours
DESCENT
AIRCRAFT SPEED - KNOTS
250
150
50
SHP/ENGINE
300
250
200
150
100
50

Figure 1

STUDY AIRCRAFT/ENGINE INSTALLATION

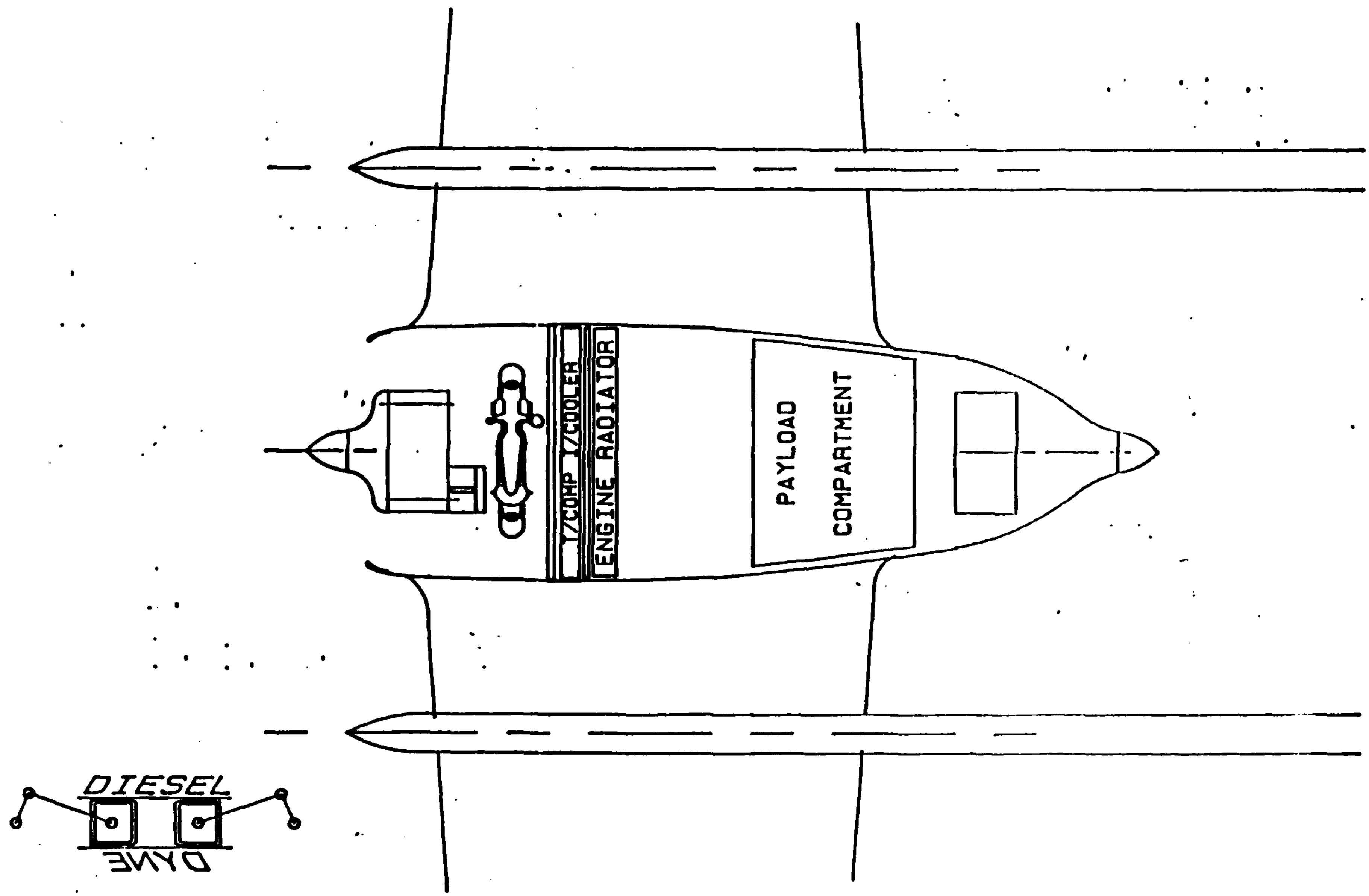


Figure 2

PROPULSION SYSTEM SCHEMATIC

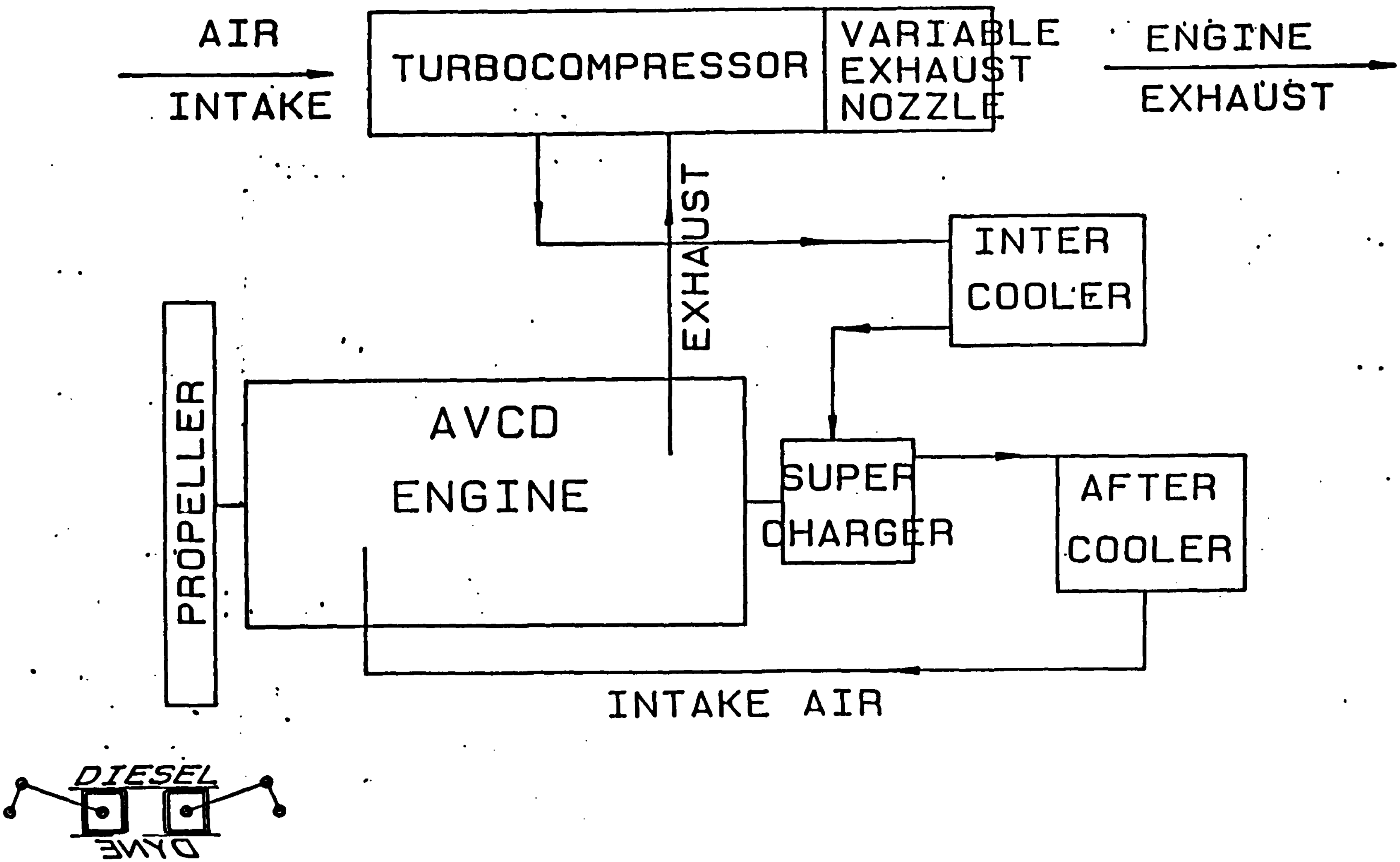


Figure 3

AVCD ENGINE

TYPICAL CROSS SECTION

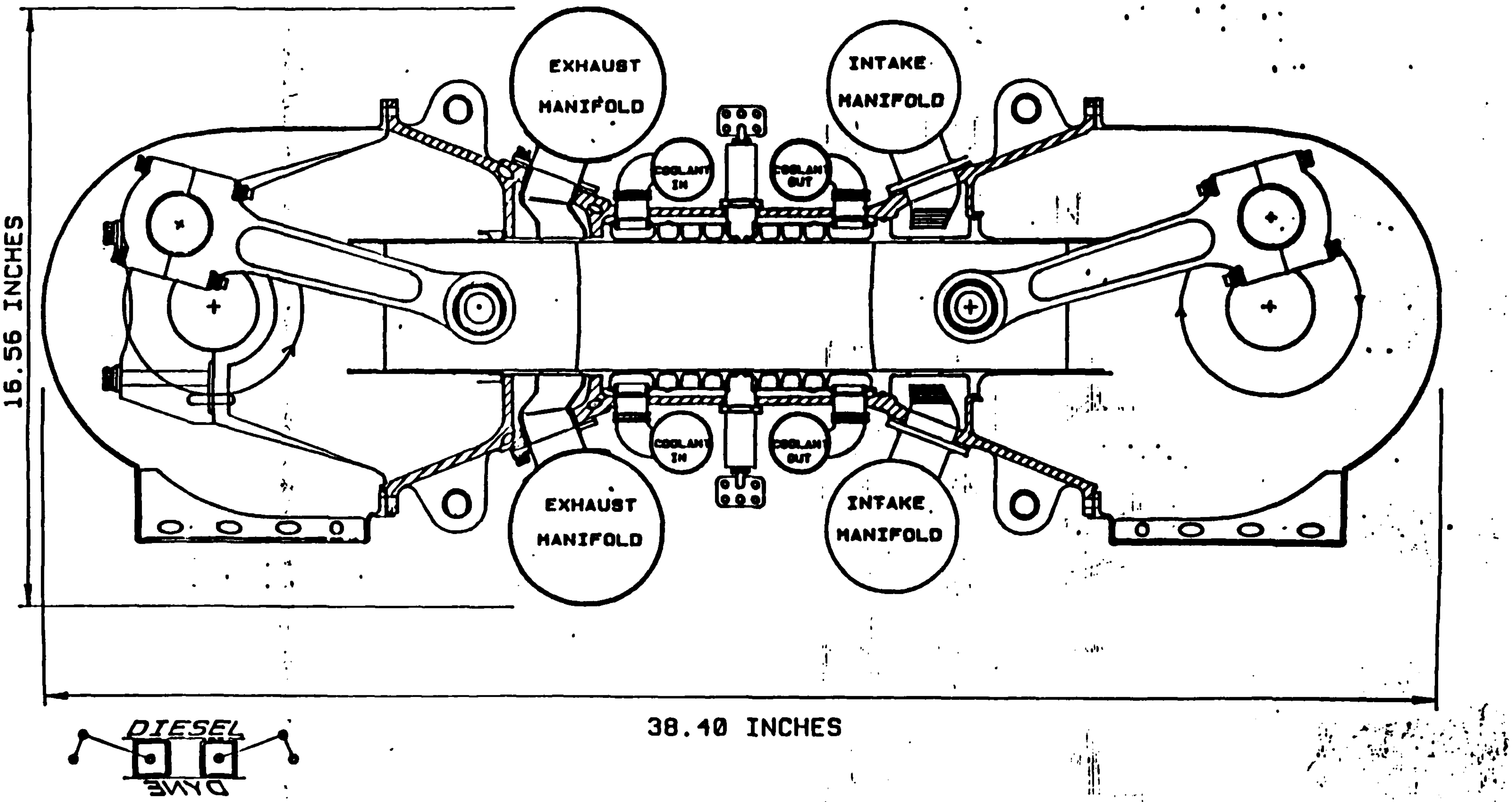
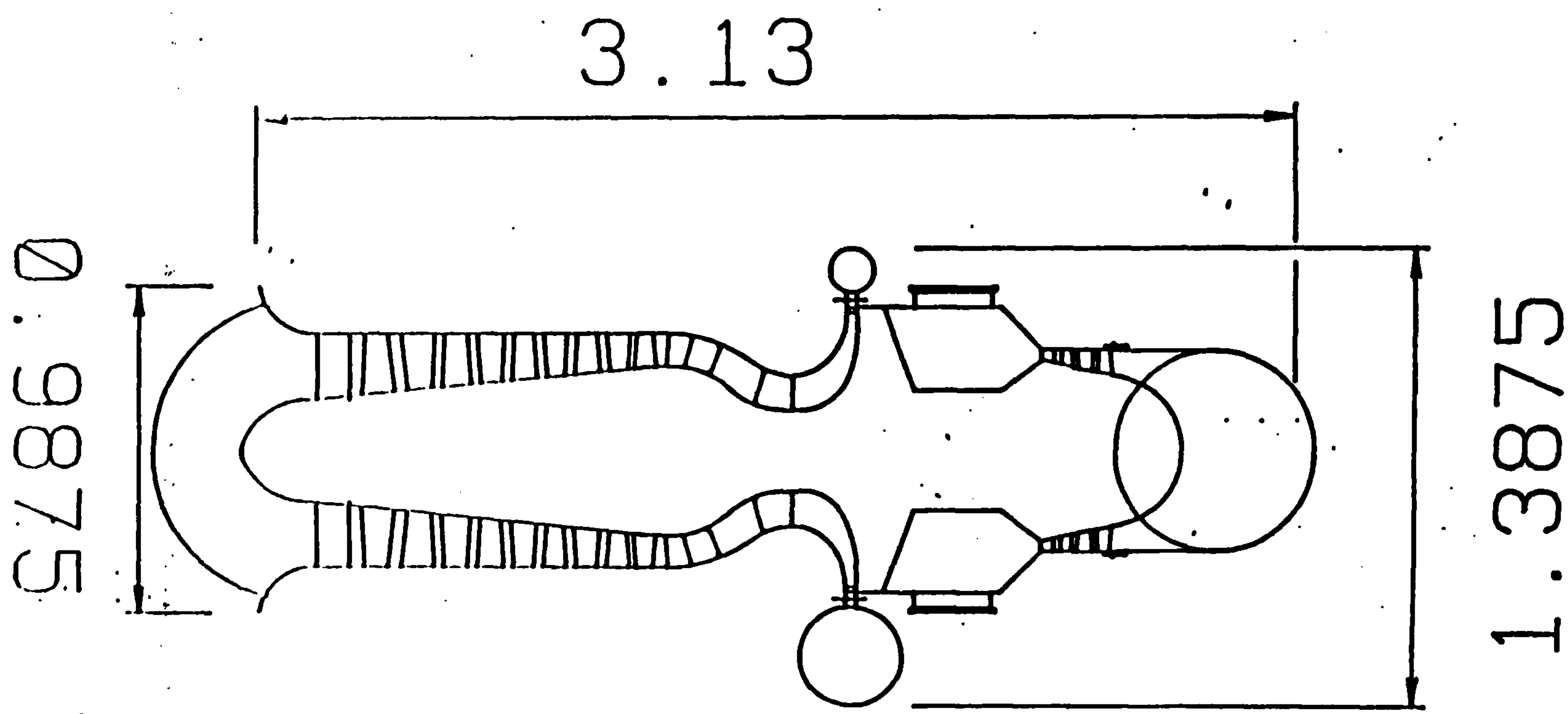


Figure 4

TURBOCOMPRESSOR



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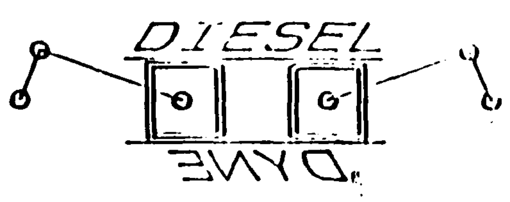
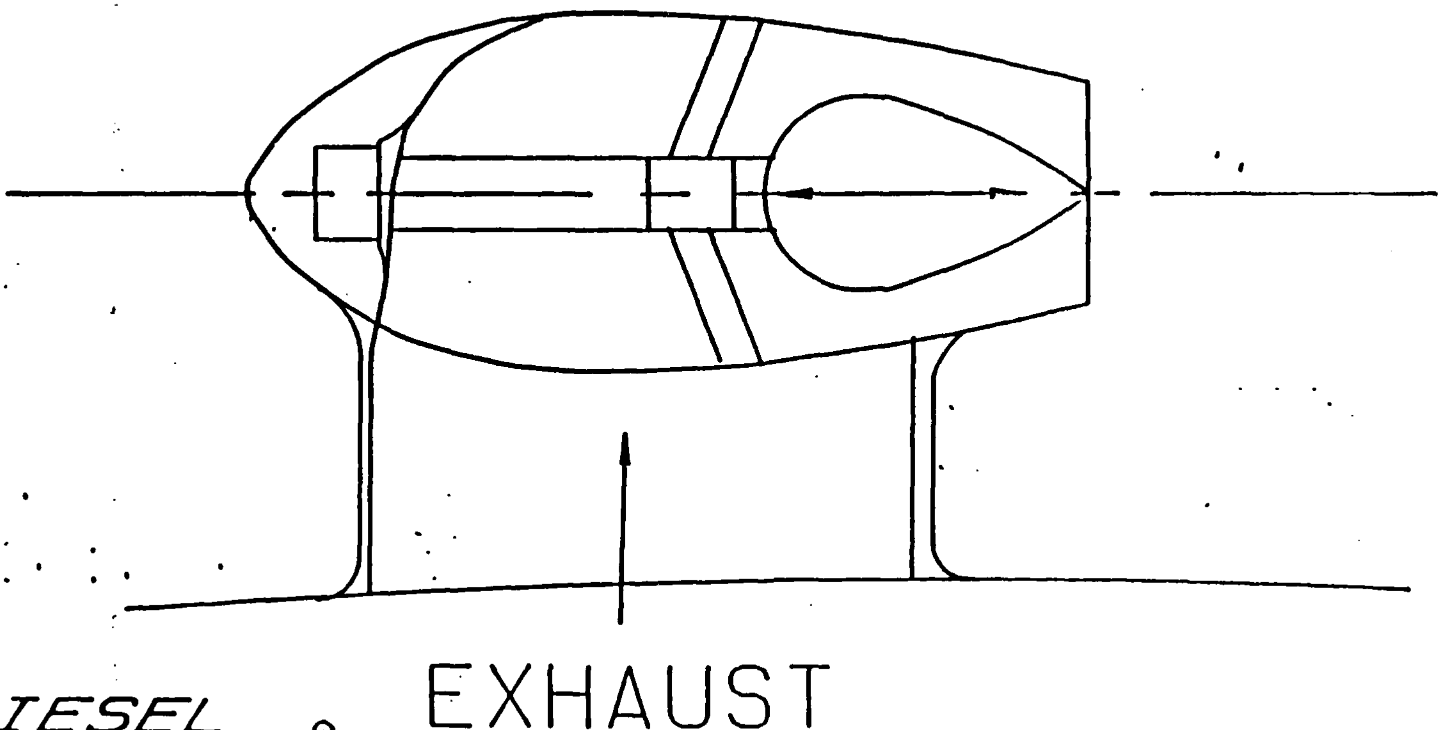


Figure 5

VARIABLE AREA NOZZLE



DIESEL
DYNE

Figure 6

ALTITUDE ENGINE CONTROL PHILOSOPHY

- COMPRESSION RATIO SET AS:
  F(RPM, M. PRESSURE, ALTITUDE, POWER)
- INJECTOR TIMING SET AS:
  F(RPM, POWER)
- BACK PRESSURE RATIO SET AS:
  F(PURGE FLOW)
- SUPERCHARGER OPERATION SET AS:
  F(ALTITUDE, POWER)

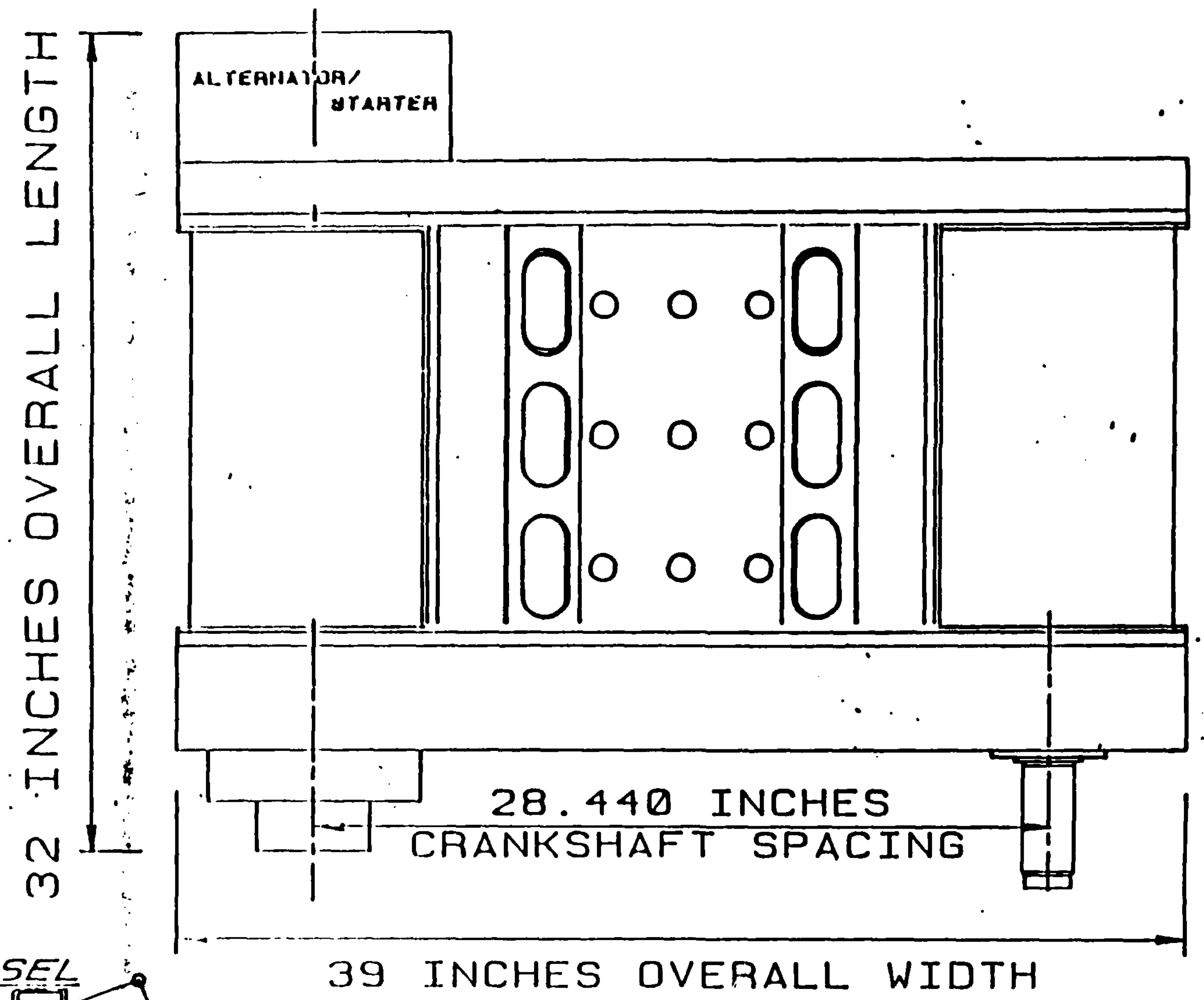
Figure 7

ENGINES STUDIED FOR 65000' MISSION

	A	B	C urrent
NR OF CYLINDERS	1	2	3
BORE/STROKE – INCHES	3.5/4.85	→	→
FLTIDLE/MAX RPM	720/3600	→	→
MAX. COMP. RATIO	60:1	70:1	→
T/COMPRESSOR 100% P/P	24:1	16:1	12:1
100 % CORR. FLOW – LBS/SEC	10	9	8
TURBINE 100 % P/P	64:1	9:1	→
100 % CORR. FLOW – LBS/SEC	.9	1.65	1.6
S/CHARGER 100 % P/P	1.7:1	1.4:1	1.3:1
100 % CORR. FLOW – LBS/SEC	.5	.6	.7
I/C EFFECTIVENESS – %	80	→	→
A/C EFFECTIVENESS – %	80	→	→

Figure 8

ENGINE DIMENSIONS



DIESEL DYNE

Figure 9

MISSION FUEL BURN COMPARISON

(FUEL - LBS)

MISSION SEGMENT	A	B	Current
T/O AND CLIMB	320.5	327.1	278.0
CRUISE TO ROA	888.0	896.8	845.2
LOITER	7106.4	5544.1	5192.2
RETURN FROM ROA	334.0	334.2	348.6
DESCENT	8.5	12.7	12.7
TOTALS	8658.1	7114.9	6676.7
Δ ENGINE WEIGHT - LBS	BASE	+216	+432
Δ T/COMPRESSOR - LBS	BASE	-44	-88
TOTALS	8658.1	7286.9	7020.7

DIESEL DYNE

Figure 10

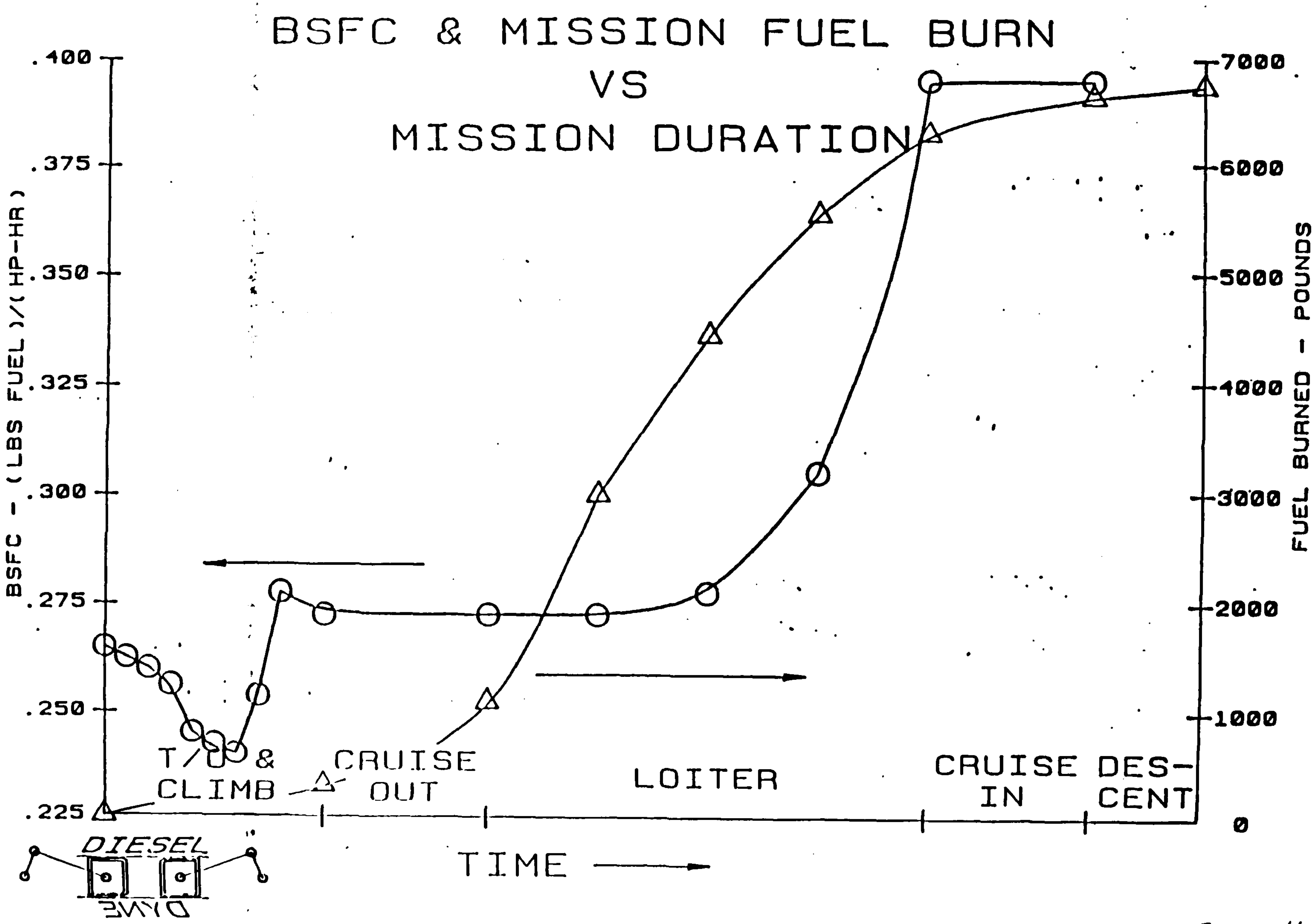

BSFC & MISSION FUEL BURN
VS
MISSION DURATION
BSFC - (LBS FUEL)/(HP-HR)
.400
.375
.350
.325
.300
.275
.250
.225
FUEL BURNED - POUNDS
7000
6000
5000
4000
3000
2000
1000
0
T/O & CLIMB
CRUISE OUT
LOITER
CRUISE IN
DES-CENT
TIME
DIESEL

Figure 11

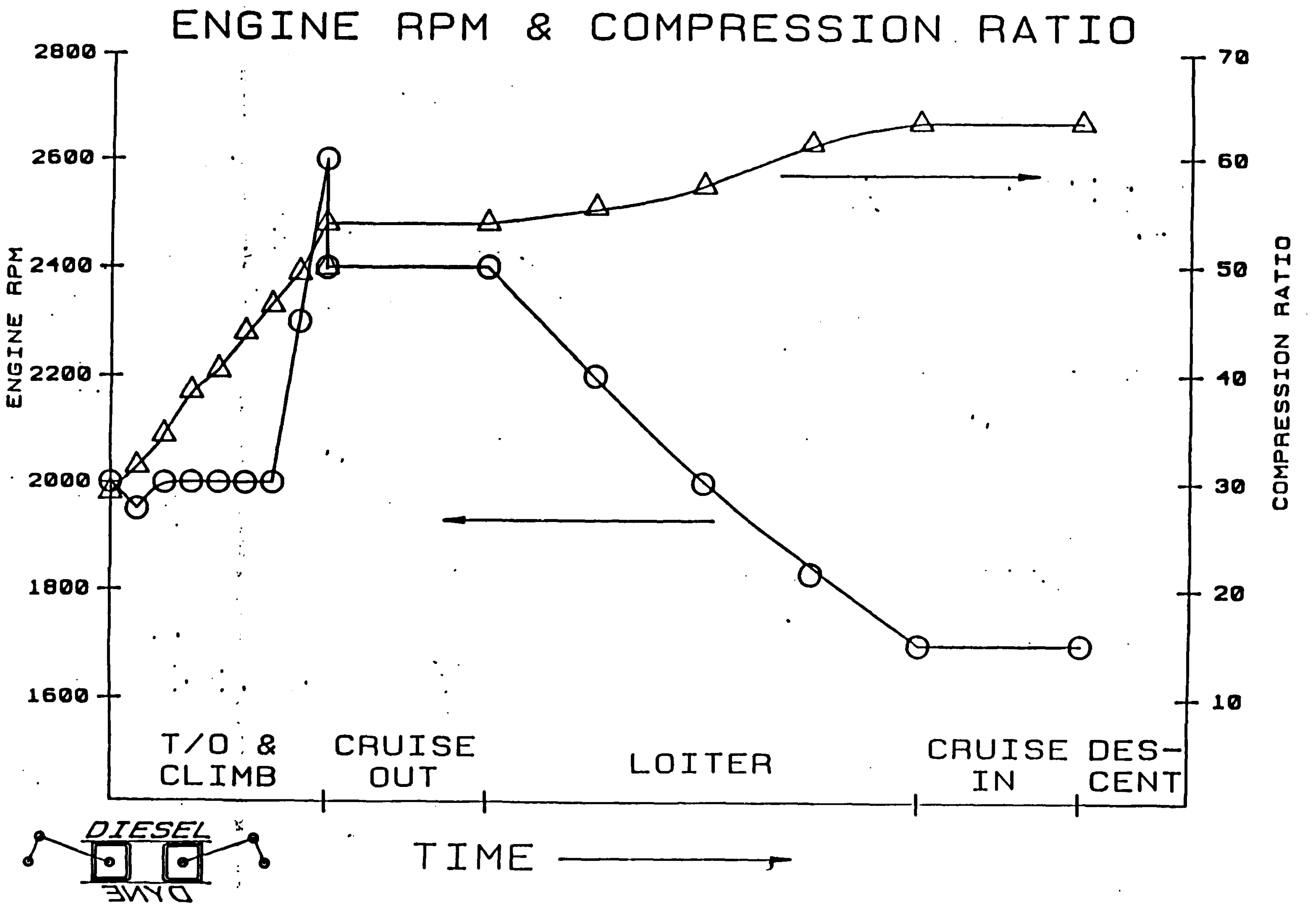

ENGINE RPM & COMPRESSION RATIO
ENGINE RPM
2800
2600
2400
2200
2000
1800
1600
COMPRESSION RATIO
70
60
50
40
30
20
10
T/O & CLIMB
CRUISE OUT
LOITER
CRUISE IN
DES-CENT
TIME
DIESEL
DYNE

Figure 12

MANIFOLD BLEED PRESSURE AND TEMPERATURE

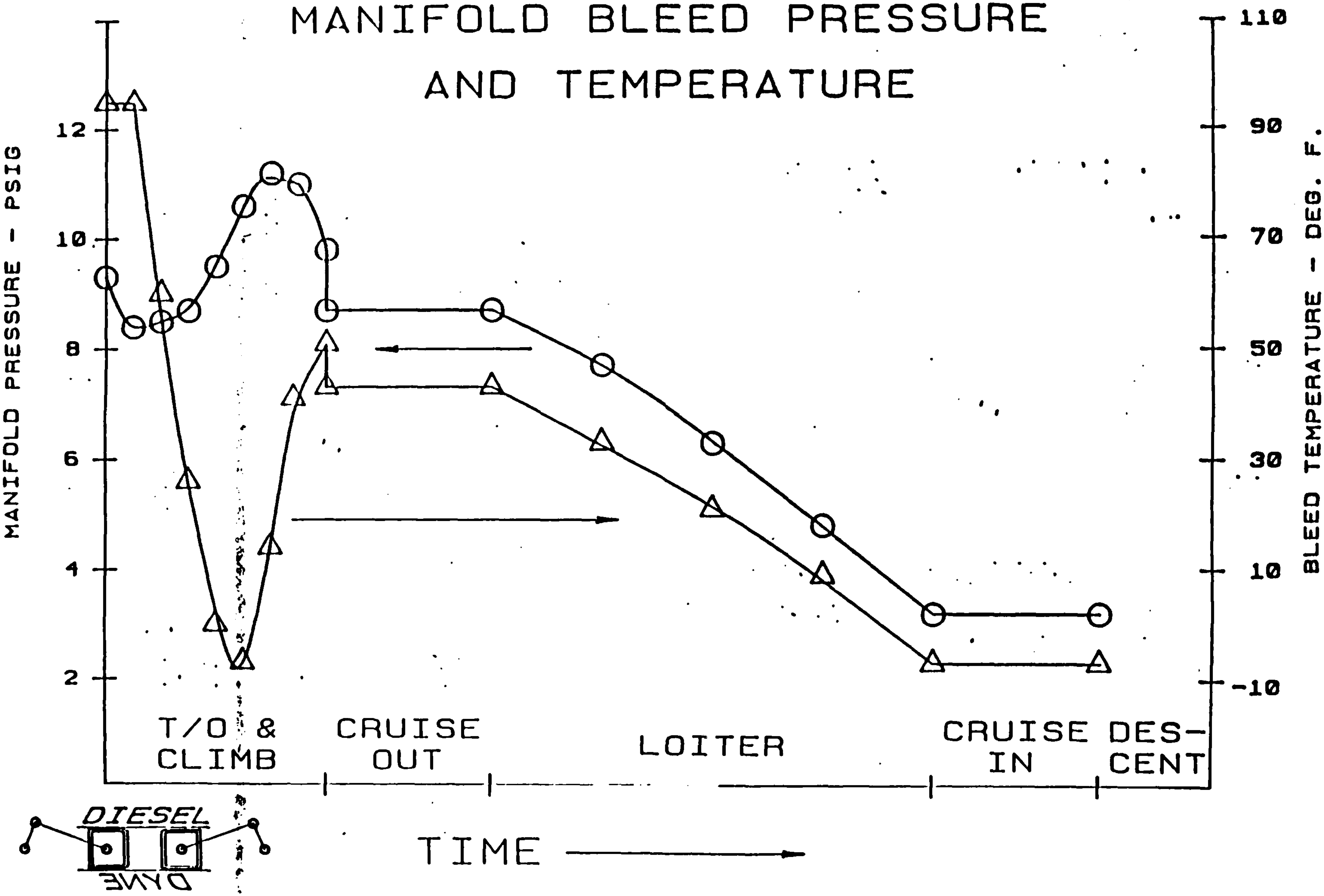
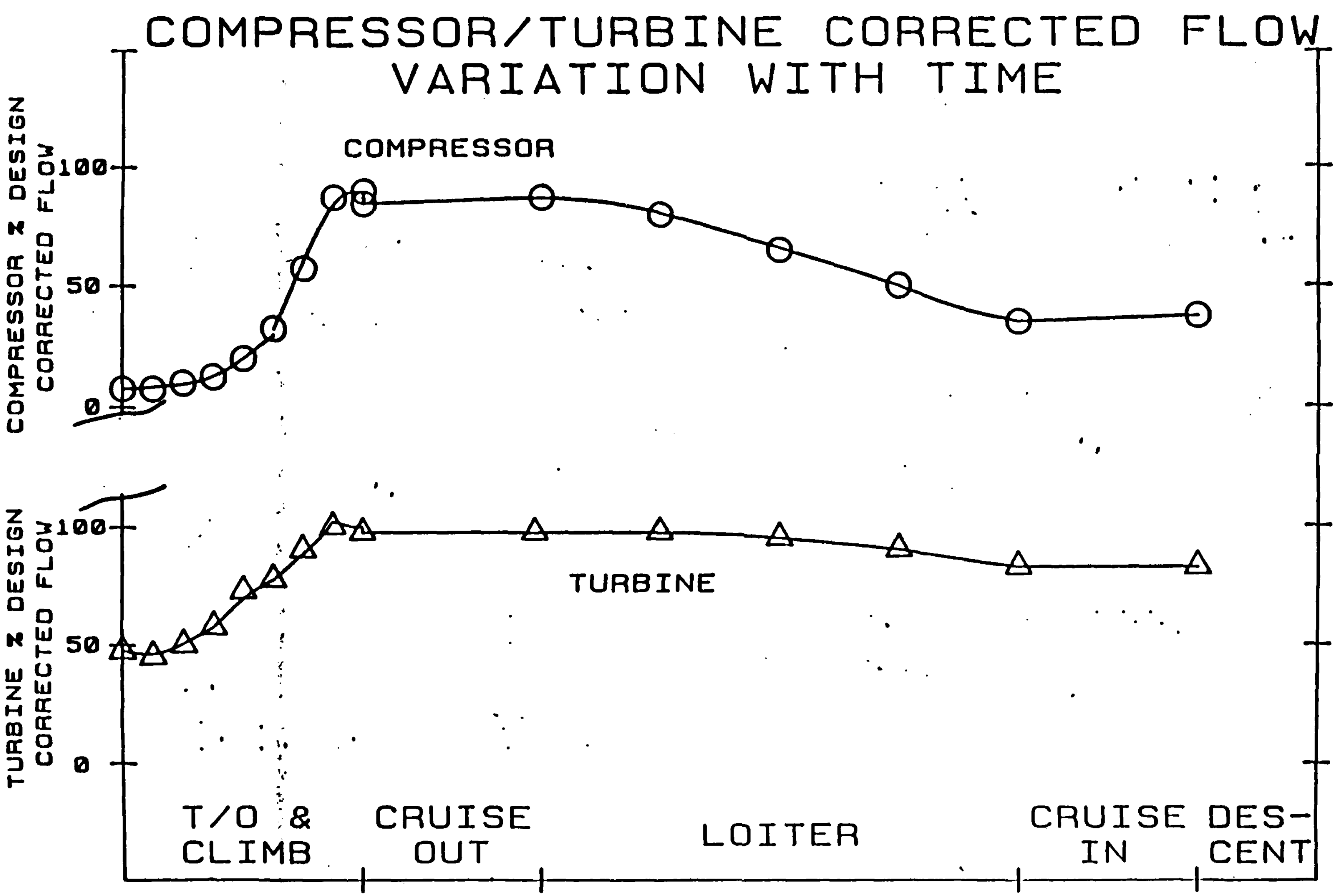


Figure 13



DIESEL DYNE

Figure 14

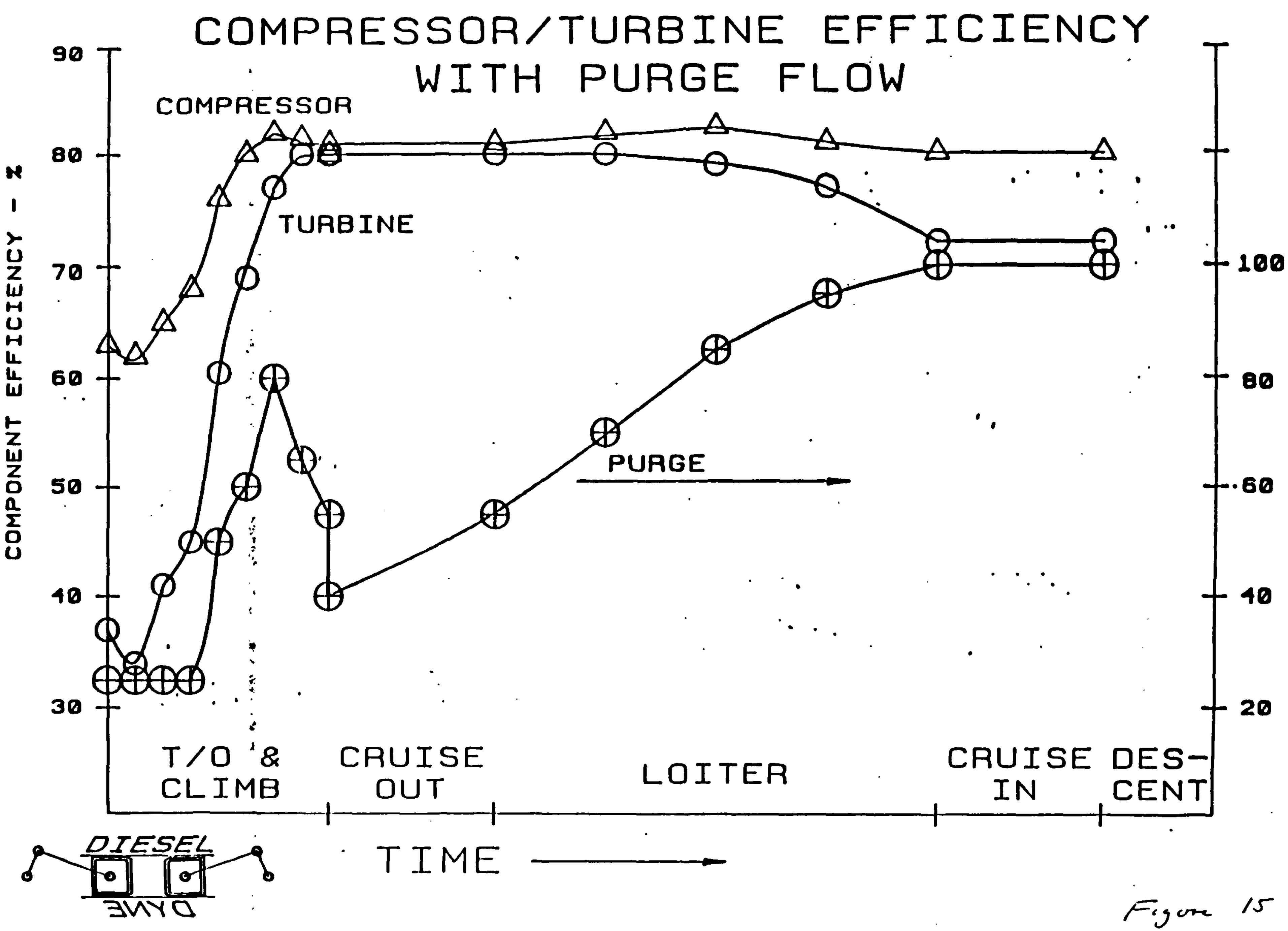

COMPRESSOR/TURBINE EFFICIENCY
WITH PURGE FLOW
COMPRESSOR
TURBINE
PURGE
COMPONENT EFFICIENCY - %
EXCESS PURGE AIR - %
90
80
70
60
50
40
30
100
80
60
40
20
T/O & CLIMB
CRUISE OUT
LOITER
CRUISE IN
DES-CENT
TIME
DIESEL
DYNE

Figure 15

NOZZLE P/R & THRUST VARIATION WITH TIME

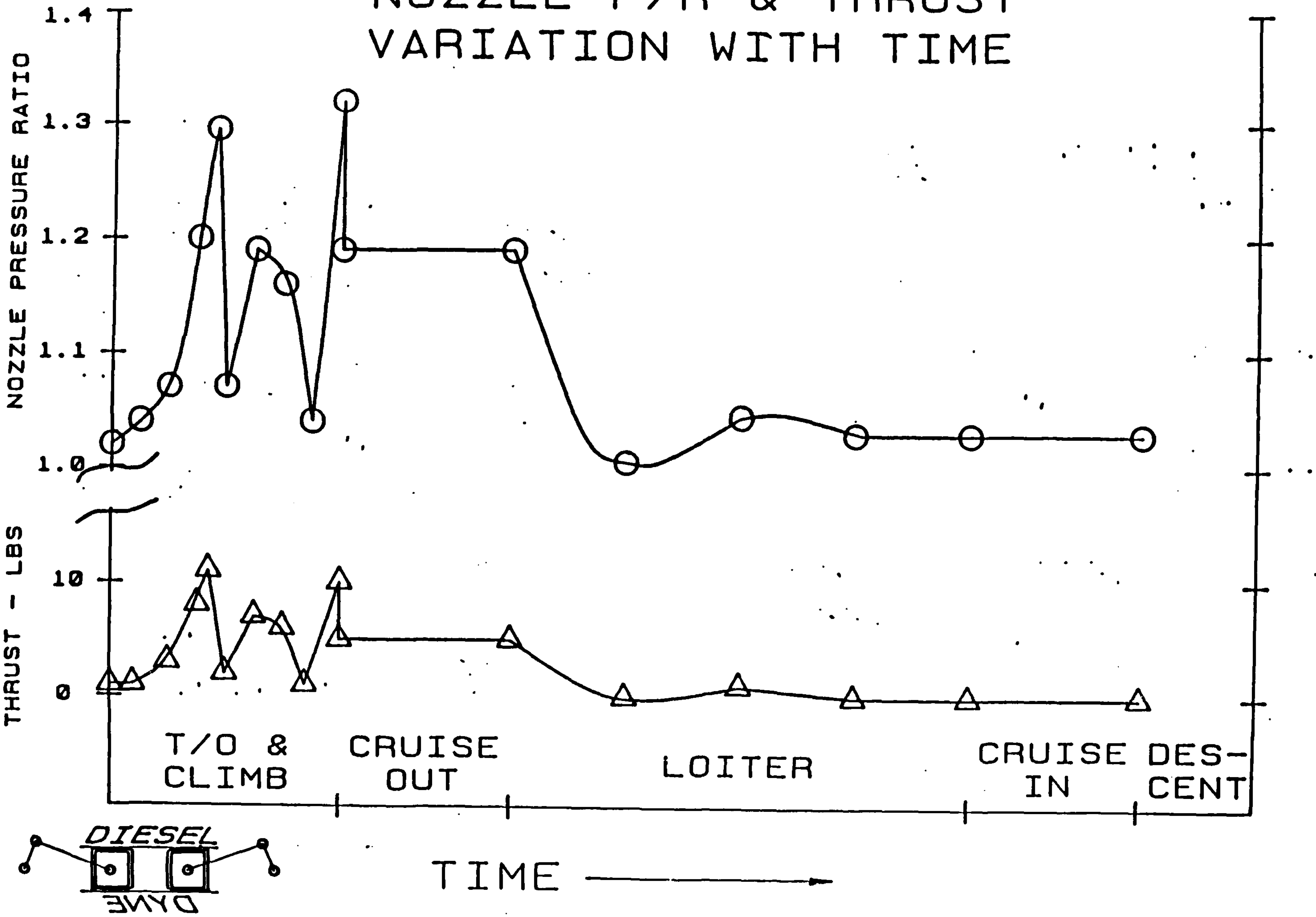


Figure 16

MAXIMUM COMPRESSION - COMBUSTION PRESSURES AND CONNECTING ROD LOADS

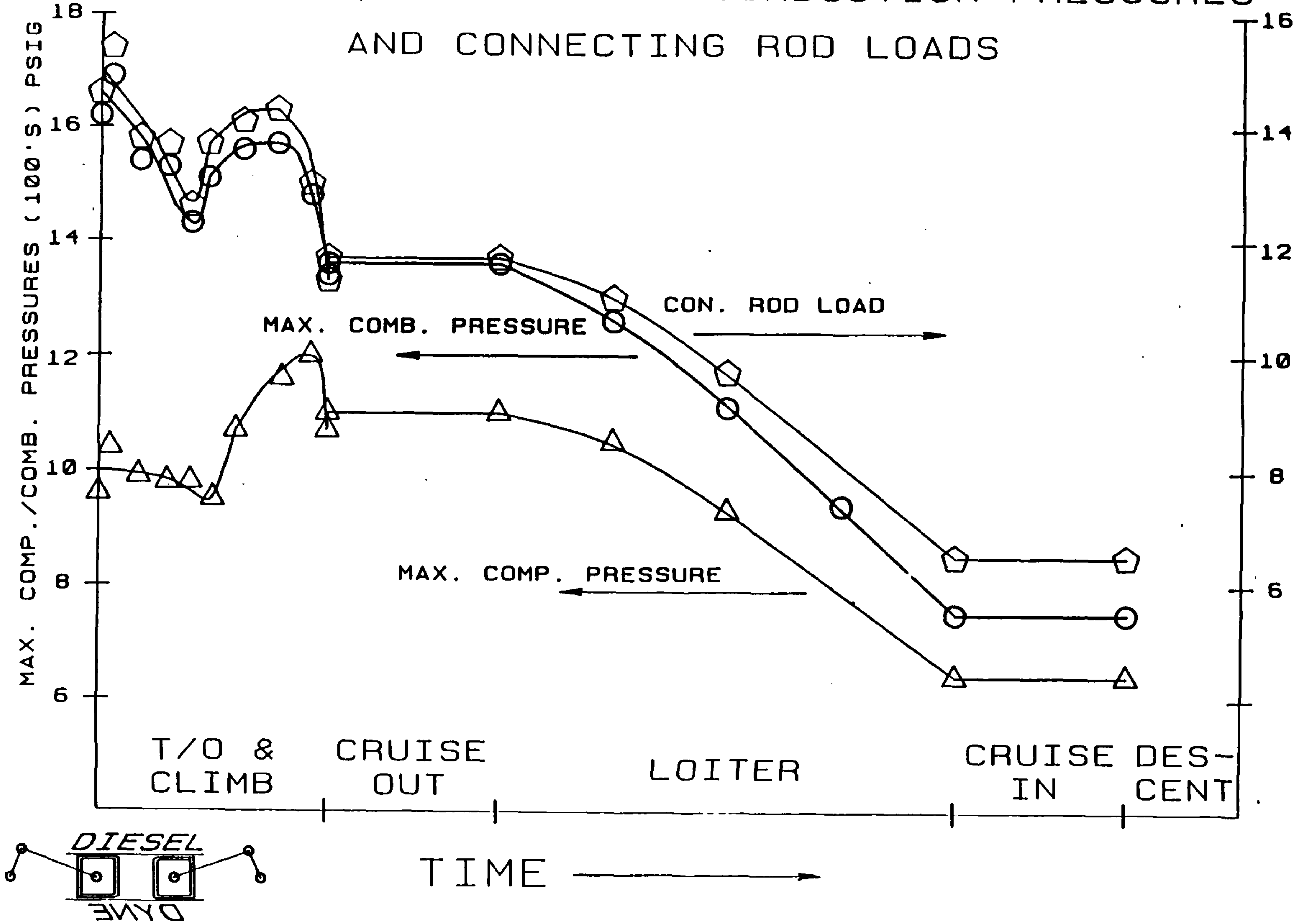


Figure 17

PRELIMINARY 65K ENGINE SYSTEM WEIGHT ESTIMATE

ENGINE	LBS	AUX. EQUIPMENT	LBS
BLOCK	116.7	ROOTS BLOWER	42.3
LINERS	46.8	FUEL SYSTEM	19.0
PISTONS/RODS	78.0	STATOR/ALT.	20.0
CRANKSHAFTS	113.4	COOLANT SYSTEM	15.5
TIMING GEARS/COVER	65.6	OIL SYSTEM	14.0
BRGS./SEALS/ETC.	25.1	MOUNTS	5.0
INTAKE/EXH SYSTEM	12.0		
ACC. CASE	17.8		
MISC.	8.0		
TOTAL	483.4	TOTAL	115.8

TOTAL SYSTEM WEIGHT - 599.2 LBS

DIESEL DYNE

Figure 18

85000 FOOT ENGINE DESCRIPTION

NR OF CYLINDERS	3
BORE/STROKE - INCHES	3.5/4.85
FLT IDLE/MAX RPM	720/3600
MAX COMP RATIO	80:1
T/COMPRESSOR 100% P/P	24:1
FLOW SIZE - LBS/SEC CORR.	20
TURBINE 100% P/P	27:1
FLOW SIZE - LBS/SEC CORR.	1.1
S/CHARGER 100% P/P	1.7:1
FLOW SIZE - LBS/SEC CORR.	1.5
T/COMPRESSOR STAGING	6 AX/1 CF
TURBINE STAGING	3 AX
COOLER EFFECT - %	80

Figure 19

SOME SPOT POINT COMPARISONS
(SFC)

	65K	85K
SLTO - 300SHP	.265	.310
MAX CLIMB, 40K	.243	.240
MAX CLIMB, TOP	.279	.282

Figure 20

AVCD ADVANTAGE OVER CONVENTIONAL ENGINE
(85000 FOOT ENGINE)

	AVCD	GTSIOL-300*
PRE-COMPRESSION - P/P	34.3:1	51.0:1
NR. COMPRESSORS	2	3
NR. TURBINES	1	4
TURBO COMPOUNDED	NO	YES
WASTEGATE	NO	YES
REQUIRED COMP. EFF. - %	83.6/80	84.5 → 88
REQUIRED TURB. EFF. - %	79.5	87
SHP	250	227
EXHAUST THRUST - LBS	24	0
EQUIV. THRUST HP	27	0
EQUIV. BSFC	.255	.26

DIESEL DYNE

* FROM TRA REPORT AFWAL-TR-87-3044

Figure 21

APPENDIX C

DIESEL DYNE

LYTRON
INCORPORATED
Engineered thermal products

November 22, 1988

Mr. Richard Johnson
DieselDyne Corporation
3044 Middleboro Road
Morrow, OH 45152

Dear Mr. Johnson:

Per your request and technical package which you sent to us, enclosed is a technical ROM for your feasibility study. Page 1 of the technical data is for a HX which is 12 ft. long X 3 ft. high, and Page 2 is for a HX which is 10 ft. long X 3 ft. high.

I hope this is sufficient for your needs and will be able to help you complete your study.

Yours truly,

Mark Audette

Mark Audette
Sales Engineer

MA:mw

Enclosure

DRAGON COURT / WOBURN, MASSACHUSETTS 01801 / TELEPHONE 617 933-7300

LYTRON
INCORPORATED
Dragon Court
Woburn, MA 01801
(617) 933-7300

JOB/QUOTE NO.: NEW CUSTOMER: DIESELDYNE DATE: 11-18-1988 ENGR JGB

DESIGN DATA

CORE CODE M 120 . 1 . 12 - 36

FINTUBE PATTERN	M	NO. OF TUBES PER ROW	%120
TUBE MATERIAL	SS	NO. OF ROWS DEEP	1
OUTER FIN MATERIAL	AL	TUBE LENGTH (INCHES)	36.0
FINS PER INCH	12	NUMBER OF CIRCUITS	60
FIN THICKNESS	0.008	NUMBER OF CROSSES	2

PERFORMANCE DATA

OVERALL UA..	1010	BTU/HR-F
HEAT REJ..	331481	BTU/HR
CORE WEIGHT.	60.54	LBS.

	FIN SIDE	TUBE SIDE
FLUID	AIR	AIR
FLOW (55#/sec)	10000 LBM/HR	1980 LBM/HR
INLET TEMP	-60.0 F	747.0 F
OUTLET TEMP	77.7 F	69.2 F
INLET PRES	0.3 PSIA	45 PSIA
DELTA P	0.41 IN H2O	2.1 PSI

DETAILED DATA

QUANTITY	FIN SIDE	TUBE SIDE
REYNOLDS NUMBER	609	23985
CHARACTERISTIC DIAMETER, FT	.03350	.02792
FREE FLOW AREA, FT^2	%12.4210	0.0367
SURFACE AREA, FT^2	407.3	31.56
PROPERTIES TEMPERATURE, F	70.0	400.0
DENSITY, LBM/FT^3	0.0016	0.1414
VISCOSITY, LBM/HR-FT	0.0443	0.0628
THERMAL COND., BTU/HR-FT-F	0.0147	0.0222
SPECIFIC HEAT, BTU/LBM-F	0.241	0.247
PRANDTL NUMBER	0.7233	0.6990
FRICTION FACTOR, F	0.1359	0.0064
COLBURN FACTOR, J	0.0287	0.0031
FIN EFFICIENCY	0.957	
HEAT TRAN COEF, B/HR-FT^2-F	6.9	51.8
TOTAL CONDUCTANCE,HA B/HR-F	2687	1635

LYTRON
INCORPORATED
Dragon Court
Woburn, MA 01801
(617) 933-7300

JOB/QUOTE NO.: NEW DIES CUSTOMER: DIES DATE: 11-18-1988 ENGR JGB

DESIGN DATA

CORE CODE M 100 . 1 . 12 - 36

FINTUBE PATTERN	M	NO. OF TUBES PER ROW	%100
TUBE MATERIAL	SS	NO. OF ROWS DEEP	1
OUTER FIN MATERIAL	AL	TUBE LENGTH (INCHES)	36.0
FINS PER INCH	12	NUMBER OF CIRCUITS	20
FIN THICKNESS	0.008	NUMBER OF CROSSES	5

PERFORMANCE DATA

OVERALL UA..	2267 BTU/HR-F
HEAT REJ..	242610 BTU/HR
CORE WEIGHT.	50.45 LBS.

	FIN SIDE	TUBE SIDE
FLUID	AIR	EG/W 50%
FLOW (43'/sec)	10000 LBM/HR	10000 LBM/HR
INLET TEMP	0.0 F	175.0 F
OUTLET TEMP	100.5 F	147.8 F
INLET PRES	0.3 PSIA	50 PSIA
DELTA P	0.63 IN H2O	2.1 PSI

DETAILED DATA

QUANTITY	FIN SIDE	TUBE SIDE
REYNOLDS NUMBER	658	19522
CHARACTERISTIC DIAMETER, FT	.03350	.02792
FREE FLOW AREA, FT^2	%10.3508	0.0122
SURFACE AREA, FT^2	339.4	26.30
PROPERTIES TEMPERATURE, F	150.0	260.0
DENSITY, LBM/FT^3	0.0014	61.6
VISCOSITY, LBM/HR-FT	0.0492	1.1687
THERMAL COND., BTU/HR-FT-F	0.0166	0.2313
SPECIFIC HEAT, BTU/LBM-F	0.241	0.893
PRANDTL NUMBER	0.7150	4.5132
FRICTION FACTOR, F	0.1283	0.0067
COLBURN FACTOR, J	0.0273	0.0032
FIN EFFICIENCY	0.952	
HEAT TRAN COEF, B/HR-FT^2-F	8.0	848.2
TOTAL CONDUCTANCE,HA B/HR-F	2576	22306